



Prefabricated Refractory Panels for Use in KSC's Flame Deflectors: A Feasibility Study

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ABBREVIATIONS AND ACRONYMS

A	ampere, Al_2O_3
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACI	American Concrete Institute
AEA	air-entraining admixture
AH_3	gibbsite
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASR	alkali-silica reaction
ASTM	American Society of Testing and Materials
BRE	Building Research Establishment
Btu	British thermal unit
C	CaO
C/C	center-to-center spacing
CAC	calcium aluminate cement
CaCO_3	calcium carbonate
CBO	Congress Budget Office
CC	conventional castables, center to center
CEV	Crew Exploratory Vehicle
CIP	cast in place
CO_2	carbon dioxide
C-S-H	calcium silicate hydrogel
D	Diffusion Coefficient
F	Fe_2O_3
FOD	foreign object debris
FSS	fixed service structure
H	H_2O
in^2/lb	square inch per pound
KSC	Kennedy Space Center
ksi	thousand pounds per square inch

lb/yd	pound per yard
LC	launch complex
LCC	low-cement castables
LRFD	Load and Resistance Factor Design
MLP	Mobile Launcher Platform
MOR	module of rupture
NASA	National Aeronautics and Space Administration
NCC	no-cement castables
PC	portland cement
pcf	pound per cubic foot
psi	pounds per square inch
PT	posttensioned
PTL	posttensioned liner
RCCP	Refractory Concrete Closure-Pour Panel
RCP	Refractory Concrete Panel
RSS	Rotating Service Structure
\bar{S}	SO ₃
SCM	supplementary cementing material
SRB	solid rocket booster
ULCC	ultralow-cement castables
VAB	Vehicle Assembly Building
w/c	water to cementitious materials ratio
a	depth of stress block
A_{ps}	area of each prestressing strand
A_s	area of flexural steel
$f_{applied}$	applied compressive stress
f'_c	concrete strength
f_{pe}	effective prestress on each strand
f_y	yield strength
jd	moment arm
M_u	ultimate bending moment
$N_{strands}$	number of strands required per slab

P_{eff}	effective prestressing force
V_u	ultimate shear force
w_u	total factored weight of the slab
ϕM_n	calculated moment capacity
ϕV_c	the nominal shear strength, provided by the plain concrete
ϕV_n	calculated nominal shear strength

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ABSTRACT

The launch complexes at the John F. Kennedy Space Center (KSC) have been used to launch space vehicles for the Apollo and Space Shuttle programs. NASA is currently designing and developing a new space vehicle. The launch complexes have been in service for a significant duration and the aggressive conditions of the Florida coast and the launches have resulted in failures within the launch complexes. Of particular interests is the performance of the refractory lining that covers the steel base structure for the diversion of the exhaust from the launched vehicles (i.e., the flame deflectors). An unprotected steel base structure would likely experience loss of strength and possible failure when subjected to the high temperatures during launches. The refractory lining is critical for successful launches.

The refractory material currently used in the flame trenches was developed in 1959 and is the only refractory material approved for use in these facilities. Significant effort and costs are expended in repairing the lining system after each launch. NASA is currently performing a comprehensive research program to assess and develop refractory materials for improved performance in the flame trenches. However, one challenge associated with the use of refractory materials in the flame trench is that the materials should be cured, dried, and fired to maximize their properties and characteristics. Because of the large size of the deflectors and trenches, drying and firing of the lining system is difficult, if not impossible. Most refractory materials are dried and fired before use. Because the refractory materials used for the deflector lining cannot be dried and fired, the full potential of the materials are not being realized.

A system that could use refractory materials that could be cured, dried, and sintered in a controlled environment would likely improve the performance of the lining system. This report evaluates the feasibility of fabricating and placing prefabricated refractory panels on the deflector. Panels could be fabricated and processed off-site in a controlled environment to maximize performance. These panels could then be transported to KSC and installed on the flame deflector.

The findings of this report indicate that conventionally reinforced, prefabricated refractory panels can likely be designed, fabricated, and placed on the deflector. Posttensioning of the panels will reduce the amount of "open" joints, which can be susceptible to accelerated erosion and abrasion. The panels, produced with newer, better performing refractory materials, should exhibit lower deterioration, providing a more economical system. A method for placing the panels has been provided.

The findings of this research indicate that post-tensioned, prefabricated refractory panels can be placed on the flame deflectors and should exhibit improved performance when compared with the current method of gunning the refractories on the deflector. Further evaluation will be needed to confirm these findings. Specific focus should be placed on the performance of the joints transverse to the exhaust flow, erosion/abrasion rates of "closed" joints, uplift forces at joints transverse to the exhaust flow, development of composite action between the steel base and the refractory panels, and refractory material resistance to the launch and Florida coast environment.

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PREFABRICATED REFRACTORY PANELS FOR USE IN KSC'S FLAME DEFLECTORS: A FEASIBILITY STUDY

1 INTRODUCTION

Properly launching vehicles into space, both manned and unmanned, requires significant engineering and science knowledge. The expense and effort in launching these vehicles is significant. Critical to the success of these launches is the launch complex – the structures and facilities required to launch these vehicles. The National Aeronautics and Space Administration (NASA) maintains two launch complexes for the launching vehicles into space - launch complexes (LC) 39A and 39B. These launch complexes were originally built for the Apollo and Saturn V rockets. After the joint U.S.-Soviet Apollo-Soyuz Test Project mission of July 1975, these pads were modified to support Space Shuttle operations.

Both pads were designed to support mobile launch operations, a concept in which space vehicles are assembled and inspected in the protected environment of the Vehicle Assembly Building (VAB), then transported by large tracked vehicles to the launch pad for final processing and launch. On April 12, 1981, the first Space Shuttle was launched at LC-39A with the launch of Columbia. After 23 successful launches from LC-39A, LC-39 B was used to launch the ill-fated Challenger (January 28, 1986). LC-39B was used for Space Shuttle launches starting in September 1988 until the reactivation of LC-39A in January 9, 1990. Since this time both launch complexes have been used for Space Shuttle launches.

The Space Shuttle is scheduled for retirement in 2010, although the Congress Budget Office (CBO) has estimated that the chance of being able to launch all scheduled missions by the retirement date is only 5 to 30 percent. After the Space Shuttle is retired, the Orion Crew Exploratory Vehicle (CEV) and the Ares I launcher are anticipated to be used for future manned space exploration – the anticipated first flight for the Orion spacecraft is scheduled for September 2014. In addition to the Orion CEV and the Ares I launcher, NASA is developing an Ares V vehicle. The Ares V vehicle will be used to transport cargo into space and is anticipated to be ready for flight in 2019. Both vehicles are anticipated to be launched from LC-39.

The need for 7 additional launches (with 3 additional optional flights) before retiring the Space Shuttle and the need to refurbish and reconfigure the launch complexes present NASA with several logistical challenges. With the need to keep both the Shuttle launch schedule and the need to begin testing of the new Ares I rocket, LC-39B was removed from operations in January 2007. The major work on the reconfiguration and refurbishment is projected to occur after STS-125, scheduled for launch on May 12, 2009. The refurbishment will include removal of the rotating service structure (RSS) and the fixed service structure (FSS) required for Shuttle launches and transforming the launch area to a “clean pad.” Plans for the refurbishment or modifications to the flame deflectors have not yet been developed; however, renovation of the deteriorating deflectors, especially on the side that deflects the exhaust from the solid rocket booster (SRB) is likely required.

LC-39A supported the first 24 Shuttle launches and because of these ongoing refurbishments, LC-39B will support all remaining launches until the Shuttle is retired. After the Shuttle is

retired, LC-39A will undergo some refurbishment and will be used as the launch pad for the Ares I rocket, as this has similar loading conditions to that of the Shuttle. Because the Ares V rocket is larger than the Ares I, additional modifications may be required to one of the launch complexes.

In general, the launch complexes (A and B) are similar in design. The general designs of these complexes will be discussed in more detail in paragraph 4. In addition to the equipment previously noted, critical to the successful launch of the space vehicle is the ability of the launch complex, or more specifically the flame deflectors, to deflect exhaust away from the space vehicle. Immediately prior to launch, the flame trench is flooded with water. Water from tanks adjacent to the launch complex is discharged onto the launch platform during lift-off – this water muffles the sound waves produced by the Shuttle engines (and soon from the Ares rockets). As the rockets are launched, the exhaust (and steam from the water) is deflected away from the launch vehicle.

These flame deflectors are constructed with a steel base system lined with a refractory cementitious material. These deflectors are critical support facilities required for the safe and successful launching of vehicles. As the number of launches increases and the exposure to the aggressive Florida coast continues, deterioration of the materials in the flame deflectors increases (Trejo et al. 2009b). Potential issues include increased probabilities of material failures – these material failures can result in the materials breaking away during a launch and becoming high-speed, foreign object debris (FOD). This FOD could jeopardize the safety of the launch complex and vehicle. Figure 1 shows an indentation in the bottom of the Mobile Launcher Platform (MLP) possibly from FOD.

To resist degradation and resulting FOD from the aggressive Florida coastal environment and the severe exhaust environment during launches and to decrease the probability of potential impact with the launch vehicle, better materials and/or systems are needed. As noted, the flame deflectors consist of a steel base structure protected with a refractory concrete lining material. The refractory material protects the steel base structure from direct exposure to the high temperature exhaust.

Refractory materials are used in structures subjected to high temperatures. These materials are commonly used to line boilers and furnaces, with many applications in the petrochemical, steel-making, and cement-making industries. There is a very wide range of applications for refractory materials with the applications and materials ranging from simple to very complex. Many conventional bricks are refractory materials – the reentry tiles on the space shuttle are also refractory materials. The complexity of the design and manufacturing of these different products, in addition to the cost for these products, varies significantly.

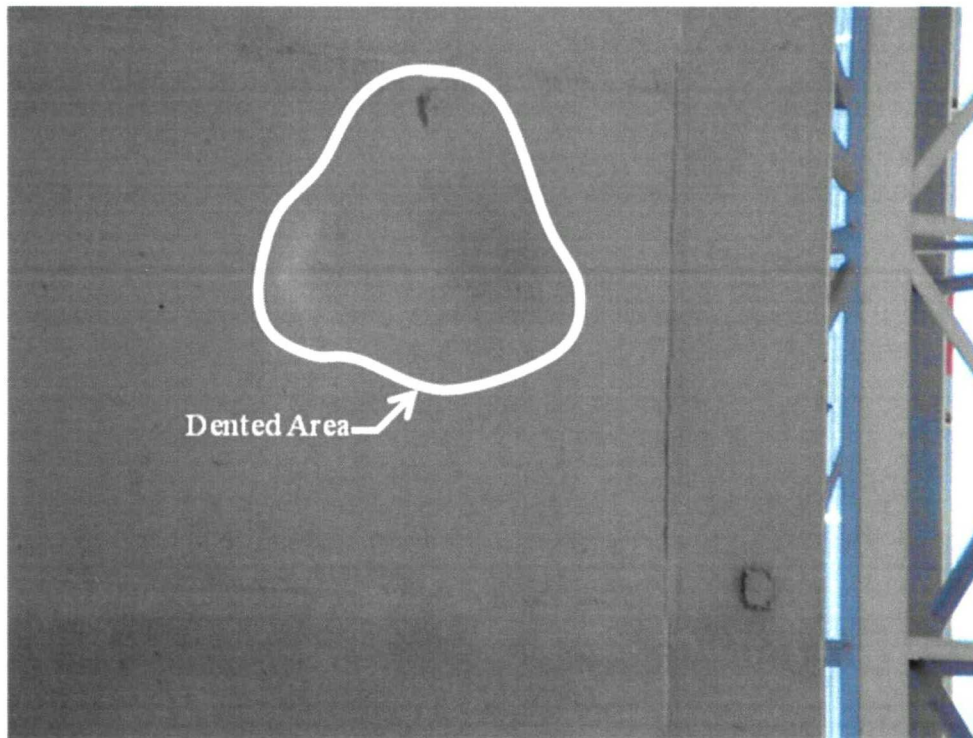


Figure 1 Photograph of indent on the bottom of the MLP possibly due to FOD

Most refractory products are processed to achieve good resistance to high temperature. Most refractory materials undergo a drying process followed by a firing process to achieve their refractoriness and improved properties. Unlike bricks, furnaces, and kilns, the refractory linings on the flame deflectors undergo no drying or firing. The large surface area of the flame trench (490 feet long, 58 feet wide, and 40 feet high) make drying and sintering very challenging, if not impossible. As a result of this, these materials cannot achieve their full performance potential and the protective lining, critical to the safe launching of space vehicles, is jeopardized.

To overcome this challenge, discussions with NASA personnel led to the hypothesis that prefabricated panels that can be dried and fired and then installed in the flame deflector may be a viable option for improving the refractory lining performance. As a result of these discussions, NASA contracted with David Trejo of Texas A&M University to review the literature on refractory products and to provide a preliminary assessment of the feasibility of using prefabricated panels to protect the steel base structure of the flame deflectors. This report includes a literature review of refractory materials and presents and discusses issues and challenges that could be associated with development of these panels. A review of calcium aluminate cements (CAC) is provided, as this material has a long history and is predominately used in refractory applications.

Although investigations at the launch complexes have identified several material deterioration problems, this report focuses only on the feasibility of fabricating and installing refractory panels for use as a protective lining on the steel base structure. A review of available refractory products will be provided with the idea of identifying potential products that could be used for the panels.

As of the writing of this report, only one refractory material was qualified for use on the flame deflectors at KSC. Several recent investigations indicated that the qualified refractory material is not performing well, and it will be assumed in this report that other materials will be considered for use in the panels.

The most recent KSC specification for refractory product was published on April 25, 1979 (KSC-SPEC-P-0012, Refractory Concrete, Specification for) (Appendix B). This specification provides requirements for refractory concretes used for heat and blast protection of the flame deflectors. The general requirements include a qualification process, required material characteristics, and minimum fresh- and hardened-material requirements. Because the existing refractory material was qualified at one time, the manufacturer is forced not to change the materials or proportions – if the materials or proportions are changed the product would have to be requalified. An analysis of test data taken to qualify potential refractory products from 1981 to 1993 indicates that all products evaluated failed to meet the requirements of KSC-SPEC-P-0012. The products evaluated included the “qualified” product that was and is currently being used in the deflectors. Trejo and Calle (2004) reported that the qualification requirements are not well defined and that potentially better performing materials have not been qualified because of these poorly defined specification tests and requirements. Trejo and Calle (2004) also recommended a preliminary suite of tests to evaluate refractory materials in the laboratory and developed preliminary qualification parameters for the potential use of refractory lining materials. Even with these potentially better performing materials, drying and sintering could likely not be performed, limiting the performance potential of these refractory products. This makes prefabricated panels – panels that can be cured, dried, and fired in a controlled environment – a potentially higher performing system for protecting the steel base structure and reducing the likelihood of FOD. However, as with many newly proposed systems, challenges do exist. This report will attempt to address challenges associated with the prefabricated panel system so that improved performance of the refractory lining can be realized. A preliminary design and constructability plan is provided to determine the feasibility of such a system.

2 CALCIUM ALUMINATE CEMENT

2.1 Introduction

This review focuses on CAC and its use in concrete applications. The review begins by describing the background and history of CAC, and then discusses the production of CAC and its hydration (and conversion) reactions. Discussions are then provided on the properties (fresh, hardened, and durability) of CAC concrete, and lastly, the combination of CAC with other binders, such as portland cement, gypsum, or supplementary cementing materials (SCMs), is summarized.

2.2 Background and History of Calcium Aluminate Cement (CAC)

CAC was invented in the early 1900's and first patented under the name “Ciment Alumineux” in 1908 by Bied. In English, the cement is known now as simply calcium aluminate cement (CAC), although it has been called over the years high-alumina cement or cement fondue. CAC was developed in response to some inherent shortcomings associated with portland cement-based products. Specifically, after the invention of portland cement by Aspdin in 1824, researchers

began searching for a binder that would provide superior durability and performance in aggressive environments, such as marine applications or where exposure to sulfates or acids was expected. Portland cement concrete can often be chemically attacked in such environments, especially due to the relative weakness and high solubility (especially at low pH values) of calcium hydroxide or “portlandite,” which is one of the main products resulting from the reaction between water and portland cement. Bied and his colleagues at Lafarge, as well as other researchers, realized that the resistance to sulfates and certain acids could be substantially improved by reducing the proportion of nondurable portlandite in the concrete mixtures. This reduction in portlandite content was made possible by reducing the proportions of calcium oxide in the cement (note calcium oxide combines with water to form portlandite), which resulted in a cement with proportionally higher aluminum oxide and silicon dioxide contents. Table 1 summarizes the typical chemical composition of portland cement, compared to CAC.

Table 1. Comparison between chemical composition of typical portland cement and typical calcium aluminate cement

Oxide	Typical Portland Cement	Typical Calcium Aluminate Cement
CaO	63	40
SiO ₂	21	5
Al ₂ O ₃	5	40
Fe ₂ O ₃	3	15
MgO	2	1
SO ₃	3	0

Typical CAC used in “technical” concrete applications; CACs used for refractory applications can have higher Al₂O₃ contents (>50 percent) and only negligible Fe₂O₃ contents (Scrivener and Capmas 1998).

It is useful to compare portland and calcium aluminate cements within a ternary phase diagram, with the main components being CaO, SiO₂, and Al₂O₃. For convenience and to remain consistent with nomenclature in cement and concrete literature, the following cement chemistry abbreviations will be used throughout the remainder of this report:

- C = CaO
- S = SiO₂
- A = Al₂O₃
- F = Fe₂O₃
- H = H₂O
- \bar{S} = SO₃

As shown in Figure 2, the chemical composition of CAC is appreciably different than portland cement-based systems. The minerals present in each binder have very little in common – portland cement is comprised of calcium silicates (C_3S and C_2S) and calcium aluminates (C_3A and C_4AF), whereas CAC is comprised primarily of CA, $C_{12}A_7$, and other minor phases. The reaction mechanisms and kinetics are vastly different, and the properties of the resultant hydration products vary in terms of rates of reaction, specific products formed, and microstructural assemblages.

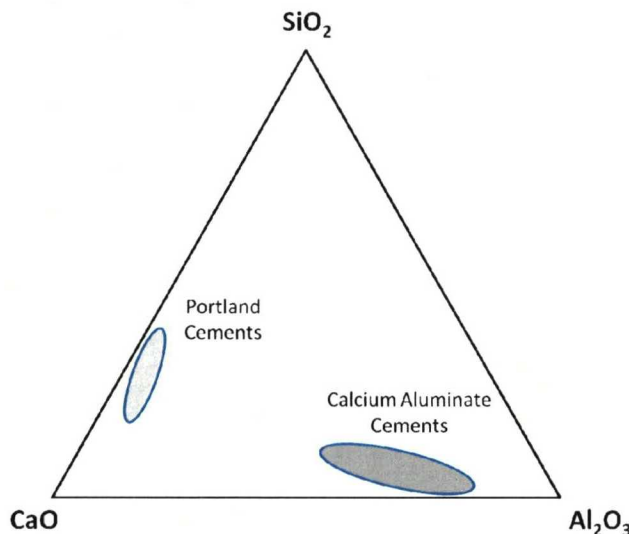


Figure 2 Ternary phase diagram comparing typical portland cement and typical calcium aluminate cement (after Scrivener 2001)

Although CAC was initially developed for enhanced durability in sulfate environments, its rapid hardening properties led to extensive use during World War I, where the rapid hardening and strength gain made it an ideal material for rapid construction (and repair) of infrastructure. Other applications and benefits of CAC that have been realized since its invention include (Scrivener 2001):

- Rapid hardening with setting times similar to those of portland cement
- Resistance to attack by acids and some other chemicals aggressive to portland cement
- Ability to withstand repeated heating to high temperatures
- Ability to withstand low temperatures in placing and use
- Resistance to abrasion and impact with appropriate aggregates

- In mixtures containing Portland cement, calcium sulfate or both, the ability to form ettringite, which can lead to controllable setting and hardening, shrinkage compensation, and combination of free water

Discussions on CAC hydration reactions are necessary in order to understand the mechanisms by which CAC can impart the above properties on concrete for field applications.

2.3 Hydration of CAC

The hydration of CAC is much more rapid than that of portland cement, and the mechanisms of these reactions are primarily linked to the rapid precipitation of calcium aluminate hydrates, which are not hindered or thwarted by diffusion barriers that develop around hydrating C_3S grains. Figure 3 shows the typical heat of hydration development of portland cement, in which can be seen the five main phases of hydration. What is of most interest is the existence of a “dormant period” or Stage 2 when portland cement hydration essentially ceases. This behavior is governed by the formation of calcium silicate hydrogel (C-S-H) around C_3S grains, which stops the dissolution of calcium and silica and reduces the availability of water to the anhydrous portion of the grain. This dormant behavior allows for concrete to be transported, placed and compacted, which are key components of concrete construction; however, this same mechanism (formation of diffusion barrier) also results in a reduced rate of strength gain, which can in some cases slow down the pace of construction.

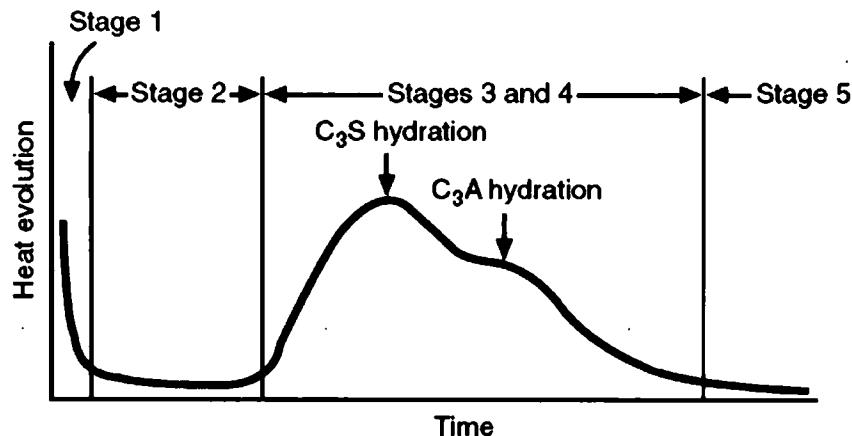


Figure 3 Hydration of portland cement – note the “dormant” behavior during Phase II, the result of the formation of diffusion barriers around reacting C_3S particles (after Kosmatka et al. 2002)

Calcium aluminates hydrate rapidly due to the absence of any diffusion barriers, thereby allowing for continuous and rapid dissolution of calcium and alumina ions and subsequent formation of calcium aluminate hydrates as part of a massive precipitation process. This process rapidly fills in voids and leads to quick and efficient hardening and strength development. Calcium and aluminate ions readily dissolve and diffuse throughout a given volume, and at some point, say two to three hours after the cement first contacts the water, solid hydration products

begin to rapidly form throughout the emerging microstructure, not just in the local vicinity of dissolving cement grains. The results are quite significant, as the concrete goes from essentially no strength when first mixed, to as high as 4,000 to 5,000 pounds per square inch (psi) compressive strength just hours later. This strength is adequate (and can meet KSC-SPEC-P-0012) for the concrete to handle most service loads and allows for rapid progression of construction and earlier project completion.

Unique to CAC is its dependence between time-temperature history and microstructure. The hydration of CAC results in the formation of stable (C_3AH_6) and/or metastable (CAH_{10} and C_2AH_8) hydrates. The thermodynamic tendency is for the formation of stable hydrate assemblages at some point in the CAC concrete's life; in the meantime, the formation of the metastable hydrates results in rapid hardening and strength gain, which are key performance characteristics that make CAC an attractive construction material.

The metastable hydrates, CAH_{10} and C_2AH_8 , form at low curing temperatures. The main metastable hydrate formed at temperatures below 59 °F is CAH_{10} (Scrivener 2001). As the curing temperature increases to near 86 °F, C_2AH_8 is also slowly formed; however, the formation of CAH_{10} is thermodynamically quite difficult in this temperature range – the overall result is a relatively sluggish reaction rate (manifested as retarded hydration). Early temperature excursions in excess of 158 °F can lead to the direct creation of stable hydrates, or the metastable hydrates are only stable for a very short period of time. Any metastable hydrates (CAH_{10} and C_2AH_8) that do form in CAC systems will eventually convert to the stable hydrates C_3AH_6 and AH_3 (gibbsite), with the time to “conversion” being dependent on the time-temperature history. For isothermal storage conditions (test cylinders stored in moist environment at fixed temperature), conversion is triggered at 100 °F in about five days and at 132 °F in about a day or two.

Scrivener and Capmas (1998) summarized the main hydration and conversion reactions for CAC, as shown below:



The hydration of CAC is quite complex – not only do different reaction products form at different temperatures, but some products that do form are metastable and are destined to convert to stable hydration products. This complete transformation in the crystal structure has a profound impact on the microstructure. The stable hydrates are about twice as dense as the metastable hydrates, resulting in a major decrease in the porosity of the system (as the volume of hydrates decreases with increasing solid density). Figure 4a shows an example of an unconverted microstructure and Figure 4b shows a converted microstructure (Ideker et al. 2008).

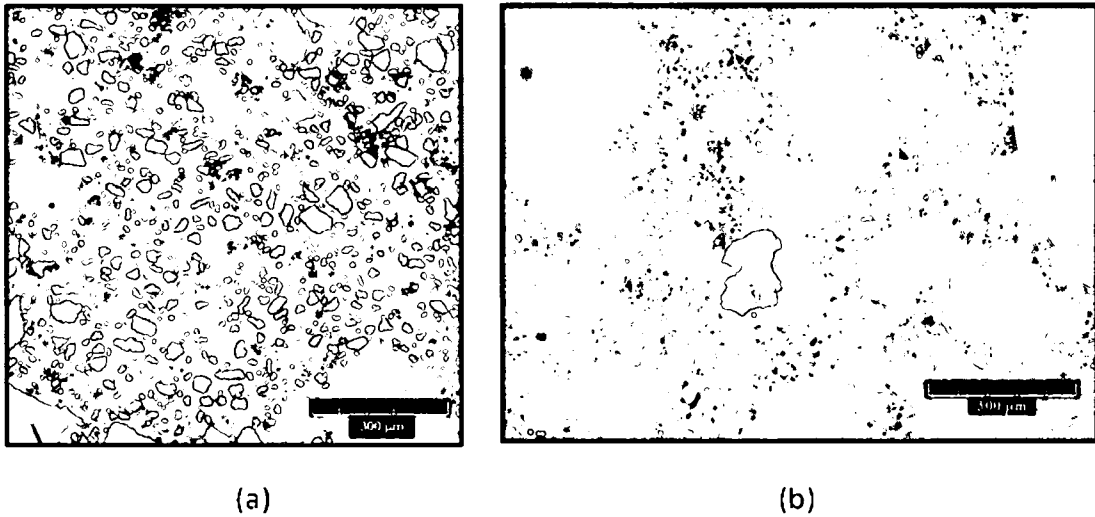


Figure 4 (a) An unconverted CAC paste microstructure (composed primarily of CAH_{10} and C_2AH_3) and (b) a converted CAC paste microstructure (composed primarily of C_3AH_6 and AH_3) (Ideker et al. 2008)

The increased porosity triggered by the conversion of CAC significantly reduces the mechanical properties of CAC concrete, including reductions in compressive strength, tensile strength, flexural strength, and elastic modulus. Upon conversion, some water is released as the metastable hydrates convert to stable hydrates. This water is subsequently recombined to form additional hydration products (stable phases), resulting in a slight strength increase. As such, the typical strength development of a CAC mixture that has undergone conversion shows the general trend illustrated in Figure 5.

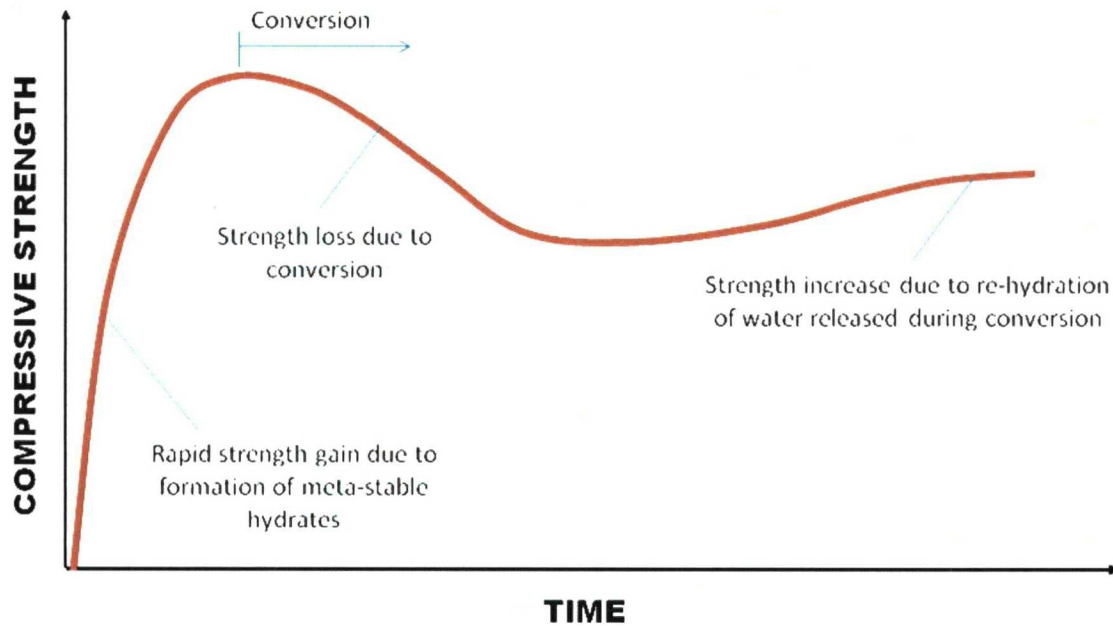


Figure 5 Plot showing typical strength development curve for CAC, illustrating rapid initial strength gain (due to formation of metastable hydrates), strength decrease due to conversion, and subsequent rehydration of anhydrous CAC with water released on conversion

Although the importance and practical implications of conversion are now clearly recognized, early users of CAC did not fully grasp the complex behavior or its impact on the structural performance of CAC concrete. As a result, several structural failures were reported in the 1960's through the 1990's – these failures resulted from users not taking into account the structural implications of conversion. In other words, users attempted to design for and take advantage of the long-term strength of the metastable hydrates; but upon conversion, the reduction in strength resulted in structural designs that were not adequate. It is now well established that conversion is inevitable, and one must design for the final, converted strengths as opposed to the transient, unconverted strength (Scrivener 2001). The key is being able to predict the minimum strength trough that accompanies conversion as this is the safe strength that can be used for structural load-carrying capacity. One way to gain an index of this “trough” behavior is to cast concrete cylinders and immediately store them in sealed containers under water at 100 °F. Conversion can then be observed within 5 days, and the lowest strength value can be recorded and incorporated into the design (Fryda et al. 2001).

2.4 Production and Properties of CAC

Modern CACs used for infrastructure applications are typically produced using a fusion method through the use of a reverberatory open-hearth furnace (Scrivener and Capmas 1998). Bauxite, primarily, and limestone are charged into this furnace through long vertical stacks. The temperature within the furnace is kept at approximately 2642 °F, sufficiently high to keep the cement in a molten state, where it is then “tapped” from the furnace and subsequently cooled and ground to a fine powder. It should be noted that this process is significantly different from the

process used for portland cement production, which involves the use of a large, rotating kiln and the addition of calcium sulfate (typically gypsum but sometimes may include anhydrous calcium sulfate).

For the production of refractory CAC, a sintering process is performed using a rotating kiln. For such products, alumina is used instead of bauxite. The raw material is selected to be free of iron oxide or silica, and the cement tends to be white in color (Scrivener and Capmas 1998). CAC produced for refractory, high-temperature exposure applications typically has an Al_2O_3 content of 60 to 80 percent. Table 2 summarizes the chemical compositions of the various CAC cements currently being produced and used in practice.

The density of CAC is typically in the range of 199 to 202 pounds per cubic foot (lb/ft^3), which is somewhat higher than portland cement (typically 196 to 197 lb/ft^3). The surface area of most CACs, typically characterized using the same method as portland cement, namely Blaine fineness, tends to be in the range of 17.6 to 28.3 square inches per pound (in^2/lb) (Scrivener and Capmas 1998).

2.5 Typical Mixture Proportions Used in CAC Concrete

There are no standardized methods for proportioning CAC concrete mixtures. However, based on a review of literature and standard practice, some trends were identified. The discussions that follow are generally based on “standard” CACs used in so-called technical concrete (e.g., repair, rehabilitation applications, etc.) and not necessarily just refractory applications.

Early applications of CAC in infrastructure applications were based on trial and error, and there was a wide range of water to cementitious materials (w/cm) ratios used for these materials. The w/cm is defined as the ratio of the weight of the water and the weight of all cementitious materials. Cementitious materials can include cement and supplementary cementing materials (fly ash, slag, silica fume, metakaolin, etc). It was found from some early structural failures that mixtures with low CAC contents and higher w/cm values tended to exhibit more pronounced increases in porosity and concomitant reductions in strength after conversion from metastable to stable hydrates, as shown in Figure 6.

As a result of these challenges, standard practice moved towards higher cement contents and lower w/cm. Specifically, the general “rule of thumb” is to specify and use a maximum w/cm of 0.40 and a minimum CAC content of 675 pounds per yard (lb/yd). The fine and coarse aggregate types and gradations are generally similar to those used in portland cement concrete. Admixtures are often used in conjunction with CAC, especially polycarboxylate-based high-range water reducers and lithium-based accelerators (to act as a trigger for hydrate precipitation).

Table 2. Chemical composition and origins of production for range of calcium aluminate cements currently available (after Scrivener and Capmas 1998)

Grade	Al ₂ O ₃	CaO	SiO ₂	Fe ₂ O ₃ + FeO	TiO ₂	MgO	Na ₂ O	K ₂ O	Color	Countries of manufacture
“Standard” low alumina	36- 42	36- 42	3-8	12-20	+<2	<1	0.1	0.15	Grey or buff to black	France, Spain, Croatia, USA, India, Eastern Europe
Low alumina, low iron	48- 60	36- 42	3-8	1-3	<2	0.1	0.1	0.15	Light buff or grey to white	France, USA, India, Korea, Brazil
Medium alumina	65- 75	25- 35	<0.5	<0.5	<0.05	0.1	<0.3	0.05	White	France, UK, USA, Japan, China, India, Korea, Brazil
High alumina	>80	<20	<0.2	<0.2	<0.05	<0.1	<0.2	0.05	White	USA, France, Brazil, Japan, Korea

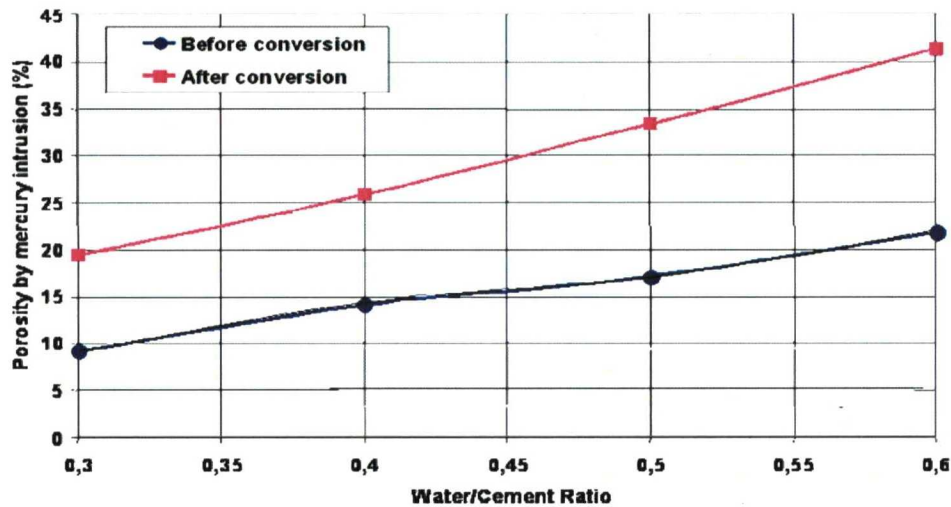


Figure 6 Effects of conversion on porosity, as function of water-cement ratio (after Cottin and Reif 1970)

2.6 Properties of CAC Concrete

This section describes the basic properties of CAC concrete, with emphasis on fresh, hardened, and durability characteristics. The focus is on concrete containing CAC as the sole binder; information on properties of concrete containing CAC in combination with other materials (e.g., portland cement, gypsum, etc.) is provided later.

2.6.1 Fresh Properties

The fresh properties of CAC concrete are not much different from those of portland cement concrete. The workability and rheological properties are governed by the same basic parameter, such as w/cm, water content, and cement content. Surprisingly, although CAC concrete hardens rapidly, its setting time is not significantly different from that of portland cement concrete. The initial set time of CAC concrete is mixture dependent and can be controlled through the use of chemical admixtures, particularly the use of lithium carbonate-based accelerators and polycarboxylate-based superplasticizers.

What is strikingly different is that the final setting time of CAC concrete quickly follows the initial set, with the time difference often being less than 30 minutes, as opposed to several hours for portland cement concrete. In modern CAC concrete mixtures, the initial set can be controlled through the use of chemical admixtures (accelerators and superplasticizers). Once initial set occurs, it is the significant precipitation of CAC hydrates, devoid of hydration or diffusion barriers that defines portland cement hydration. This quickly results in final set and strength development.

Most CAC fresh properties are similar to those of portland cement concrete and are controlled by the same variables. For example, the density (or unit weight) is controlled primarily by the

aggregates used and the air content in the mixture. CAC concrete can be produced using conventional air-entraining agents (AEAs), such as vinsol resins, gum rosins, and synthetic formulations, to develop resistance to freezing and thawing and/or salt scaling.

2.6.2 Hardened Properties

A hallmark of CAC technology is its ability to rapidly harden and develop strength, thereby making it a desirable material for repair applications, fast-track construction, and specialty construction (such as application on the flame deflectors). As previously described, the strength developed at early ages is somewhat “artificial” in that the metastable hydrates that tend to form in most situations will ultimately convert to stable hydrates, resulting in increased porosity and reduced strength. Upon conversion, the changes in the mechanical properties of CAC concrete can be quite significant; and interestingly, conversion impacts different mechanical properties to varying extents. Table 3 shows the quantitative impact of conversion on the most relevant and important mechanical properties of CAC concrete (after Lamour et al. 2001). Conversion generally seems to have a greater impact on mortar than concrete, most likely due to the higher CAC paste content. Conversion seems to have more of an impact on compressive strength than other mechanical properties. This is expected as significant work has been done that shows most other mechanical properties are correlated to the square root of the compressive strength.

Table 3. Impact of conversion on mechanical properties of CAC concrete (after Lamour et al. 2001)

Mechanical Property	Ratio Between Properties for Unconverted and Converted CAC Mortar or Concrete		
	CAC Mortars (siliceous aggregates)	CAC Concretes (siliceous aggregates)	CAC Concretes (calcareous aggregates)
Compressive Strength	2.1	1.4	1.3
Splitting Tensile Strength	2.4	1.3	1.1
Fracture Toughness	1.8	NA	NA
Elastic Modulus	NA	1.1	1.1
Poisson's Ratio	NA	1.1	1.1

Other than the unique fact that CAC concrete undergoes conversion, with a concomitant reduction in mechanical properties, the relationship between the various mechanical properties to each other tends to follow the same trends as in concrete. For example, the general relationship between compressive strength and tensile strength or compressive strength and elastic modulus follows the same general trend as in portland cement concrete, meaning that one can use the compressive strength at any point in time to predict other mechanical properties using the same predictive equations that are typically used for portland cement concrete (Lamour et al. 2001).

The early-age behavior and volume stability of CAC concrete was studied extensively in recent years (Ideker 2008; Ideker et al. 2008). The results of an extensive testing program at the University of Texas at Austin and Oregon State University have shed light on the complexities of CAC concrete with regard to early-age volume changes. Under isothermal testing (fixed

temperature) using an integrated test setup (including restrained and unrestrained beam specimens, with parallel test specimens for mechanical property testing), it was found that when the curing temperature was below 86 °F, CAC concrete would undergo autogenous shrinkage; but at curing temperatures above 86 °F, the same mixture would exhibit significant autogenous expansion. Autogenous shrinkage is defined as a volume change occurring without moisture transfer to the environment. This behavior is quite different from portland cement concrete, where autogenous shrinkage is the predominant behavior, regardless of the isothermal curing temperature. The exact mechanism responsible for CAC concrete's unique behavior is not fully understood – the expansion occurs almost from the onset of hydration and does not seem to be directly related to the conversion process. The practical implications of this behavior can be quite important. The development of autogenous expansion, if properly restrained, can be advantageous in prestressing applications and can lessen the impact of other forms of volume reduction (thermal, plastic, drying, etc.) that can result in cracking (likely a significant factor in spalling of the refractory lining in the flames deflectors at KSC).

2.6.3 Durability Properties

The durability of CAC concrete in aggressive environments has been well documented and, next to their superior refractory characteristics, is one of the most commonly cited benefits of CAC concrete. In fact, CAC concrete was initially developed with the goal of producing a building material that would exhibit superior resistance to sulfate-rich environments. This section briefly summarizes the behavior and performance of CAC concrete with regard to key durability issues and concerns, including sulfate resistance, corrosion of reinforcing steel, frost resistance, acid resistance, and alkaline hydrolysis.

2.6.3.1 Sulfate Resistance

CAC was originally developed as a material suitable for use in sulfate-rich environments, and the use of CAC concrete in aggressive sulfate environments dates back approximately 90 years. CAC concrete was used in significant amounts in the early 1900's (especially between 1916 and 1923) for various applications, including for the construction of the PLM Railway in France, which runs through gypsum and anhydrite (Touché 1926). Concrete used for this railway has performed excellent to date, with no distress observed in the structure or in test specimens immersed in gypsum solution. Similar excellent performance in a sulfate environment was reported by Miller and Mason (1933), where CAC concrete exhibited very good durability for over 20 years in the sulfate waters of Medicine Lake, South Dakota. In the same study, portland cement concrete completely failed within 5 years, and "sulfate-resistant" portland cement lost nearly half its strength after 10 years.

A comprehensive laboratory and field study was initiated by the Building Research Establishment (BRE) in the UK in 1970, with the 15-year results summarized by Crammond (1990). The w/c is defined as the ratio of the weight of the water and the weight of the cement (only). In general, when the w/c value is used it implied that no supplementary cementing materials were used in the mixture. The w/c for the concretes included in this study ranged from 0.47 to 0.60; no mixtures were cast at w/c values less than 0.4, which is the typical upper-bound limit for w/c recommended in modern CAC practice. The overall performance of CAC concrete in the BRE study was quite good, with only minimal damage after 15 years of sulfate exposure.

An interesting observation made by BRE researchers and reported by Crammond (1990) was that a dense outer layer was detected on the concrete specimens. This dense outer layer has been detected in other field structures and this dense layer, composed primarily of converted hydrates, may help to partially explain the superior performance of CAC in sulfate-rich environments. It is also possible that the lack of calcium hydroxide is a key factor in CAC concrete's ability to resist sulfate attack as calcium hydroxide is readily attacked by sulfate, resulting in the formation of water-soluble gypsum or ultimately the formation of expansive ettringite. It is also possible that although ettringite formation is expected in CAC concrete, the ettringite that forms may not be expansive in nature, perhaps due to the lower pore solution pH of CAC concrete, compared to that of portland cement concrete.

2.6.3.2 Corrosion of Reinforcing Steel

Portland cement concrete has been used extensively over the past 200 years in combination with steel reinforcement – this combination is technically viable because the pH of the pore solution (13.2 to 13.8 is typical) is high enough to lead to the formation of a passive, protective layer that forms on the surface of the steel. Values of pH above 11.5 are generally considered as passivating for reinforcing steel. Provided that chlorides do not penetrate to the surface of the steel in sufficient quantities to depassivate this protective layer and provided that the depth of carbonation does not reach the depth of the steel, reinforced portland cement concrete can remain durable for many years. Carbonation reduces the pH of the pore solution; lower pH values can lead to active corrosion of the reinforcement. The same holds true for CAC concrete, but there is one fundamental difference between portland cement and CAC concrete – the equilibrium pH of pore solution in CAC concrete tends to be lower than that of portland cement concrete, typically in the range of 12.2 to 12.4. This range (Macias et al. 1996) is still high enough to passivate reinforcing steel, but there is less of a safety factor as the pH does not need to drop as much as portland cement concrete to trigger general corrosion.

There has been very little research performed to quantify the rate of chloride ingress into CAC concrete. Macias et al. (1996) described the relevance of a dense outer layer that forms on the surface of CAC concrete, which may help to reduce the rate of chloride ingress or the depth of carbonation. It has also been proposed that the binding capacity of CAC concrete is quite high as the calcium aluminate phases are effective in binding incoming chlorides through the formation of Friedel's salt. It is not clear from published research what role conversion plays in the rate of chloride ingress, but it is clear that lower w/cm values tend to reduce the rate of chloride ingress, regardless of the nature of the hydrates present in CAC concrete.

The hydration products in CAC concrete, like those in portland cement concrete, will react with atmospheric carbon dioxide (CO_2) to form calcium carbonate (CaCO_3). In addition, both converted and unconverted CAC hydration products will also form AH_3 and water as part of the overall carbonation process (Scrivener and Capmas 1998). As carbonation occurs deeper and deeper into concrete with time and reaches the depth of reinforcement, one would expect that the carbonation, which is accompanied by copious reductions in the local pH, would result in general corrosion, as is the case for portland cement concrete. However, Dunster et al. (1996) reported that even when carbonation reaches the steel surface in CAC concrete, the actual presence of active corrosion was found to be quite rare.

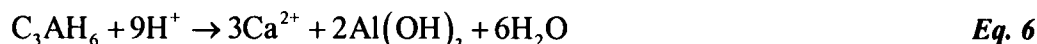
Because of the general lack of information and data on the corrosion of reinforcing steel in CAC concrete, it is difficult to make firm statements regarding the corrosion resistance of this material. More research is needed to determine and quantify the chloride diffusion through CAC concrete, the chloride threshold value needed to initiate corrosion, and the relative importance of carbonation in field elements. This is significant as the CAC refractory lining on the flame deflectors at KSC (LC-39A and B) protect a steel base structure.

2.6.3.3 Frost Resistance and Salt Scaling

CAC concrete can be produced to be resistant to frost and salt scaling, provided that a suitable air-void system is present, owing to the use of an AEA. In addition to the use of AEA, it is generally the case that CAC with water to cementitious materials ratio (w/c) values to less than 0.40 and an internal porosity less than approximately 13 percent will provide resistance to both internal frost action and external deicing salt scaling (Scrivener and Capmas 1998). The same AEAs that are used in portland cement concrete (e.g., vinsol resins, gum rosins, and synthetics) are generally suitable for entraining air in CAC concrete (Jolin and Gagnon 2008).

2.6.3.4 Acid Resistance

CAC concrete, like portland cement concrete, can be attacked by strong acids. For portland cement concrete, acids, such as sulfuric acid, will attack various hydrates, including C-S-H and calcium hydroxide, resulting in severe distress as water-soluble gypsum and a skeleton of silica are formed. CAC hydration products do not contain either C-S-H or calcium hydroxide but rather contain calcium aluminate hydrates (C_3AH_6 , C_2AH_8 , CAH_{10}) and hydrous alumina gel or gibbsite (AH_3). At pH values above 4, AH_3 is stable and durable, and the reaction between calcium aluminate hydrates and acids will lead to the following reaction (after Scrivener and Capmas 1998):



The production of $Al(OH)_3$ in the above equation results in the formation of a protective barrier that provides protection from further acid attack and dissolution.

At pH values below 4, the following reaction will occur in the presence of a strong acid, leading to the dissolution of AH_3 :



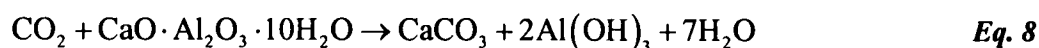
As a consequence of the above reaction, specifically the reaction between one mole of AH_3 and six moles of acid, the neutralization capacity (or the quantity of acid needed to dissolve a given quantity of cement) of CAC concrete increases (Scrivener and Capmas 1998). This increase in neutralization capacity helps to explain the superior performance of CAC concrete in a strong acidic solution. This performance at low pH values (less than 4), coupled with the formation of a protective barrier at pH values above 4 make CAC concrete a material of choice for a wide range of exposure conditions. This is particularly important in the flame trench as the hydrogen chloride from the solid rocket booster (SRB) produces hydrochloric acid when exposed to water.

One particular application where CAC concrete has been used extensively involves the use in sewage pipes. In this environment, sulfates in the sewer are converted to sulfide by bacteria. The sulfide is then released into the sewage stream and, due to movement and turbulence, the H_2S volatilizes and collects at the crown of the pipe. At this point, oxidation results in the formation of sulfur, which is consumed by an additional form of aerobic bacteria, producing H_2SO_4 as a waste product. It is this H_2SO_4 that then attacks cementitious materials. For the reasons previously described, namely the formation of a protective barrier at pH values above 4 and the increase in neutralization capacity below this pH value, that has led to the widespread use of CAC concrete in sewage applications. This resistance to acid attack is likely very beneficial for the refractory lining materials in the launch complexes as the SRBs produce hydrogen chloride. When the hydrogen chloride is exposed to water, which is present in the deflectors during the launch, the hydrogen chloride produces hydrochloric acid. The CAC refractory's resistance to acid attack is critical for the long-term performance of both the refractory lining and the steel base structure.

2.6.3.5 Alkaline Hydrolysis

Portland cement concrete is often affected by an internal chemical reaction known as alkali-silica reaction (ASR), in which the high pH pore solution leads to dissolution of certain siliceous aggregates, followed by the formation of a hygroscopic alkali-silica gel, and lastly followed by water absorption and expansion and cracking. ASR is triggered by the long-term exposure of the siliceous aggregates to the internal pore water in concrete, and this reaction can occur as long as the pH is above approximately 13.2. In the case of CAC concrete, the lower pore solution pH provides protection against ASR as silica exhibits very limited solubility in the CAC pore solution (with pH values on the order of 12.2 to 12.4). It is possible that external alkalis, in the form of NaCl-based deicing salts or seawater, could permeate into CAC concrete and potentially increase the pore solution pH, thereby triggering ASR. However, this "classical" form of ASR has never been observed in CAC concrete. There is another related issue that may be more prevalent in CAC concrete, namely alkaline hydrolysis.

Alkaline hydrolysis has been reported to occur in a limited number of field structures constructed with CAC concrete. This mechanism can be summarized by the equation below (Puertas et al. 1996), which may be catalyzed by the presence of alkalis within the concrete:



The above reaction is similar to the carbonation process that occurs in portland cement concrete. However, when this carbonation reaction occurs in CAC concrete in the presence of alkalis, a significant reduction in strength can occur, especially in CAC concrete with high porosity and relatively high w/cm values. In these cases, it is believed that the catalytic effect of alkalis tends to increase the solubility of both CO_2 and $\text{Al}(\text{OH})_3$, leading to a general dissolution and loss of cohesion of the calcium aluminate hydrates. According to Scrivener and Capmas (1998), the following four components must be active for alkaline hydrolysis to be a concern:

- a. High internal porosity (possible in CAC refractory concrete)
- b. High humidity and internal saturation (possible at the Florida coast)

- c. Presence of sufficient quantity of free alkalis (possible in the refractory used for the lining on the flame deflectors)
- d. Presence of sufficient quantity of CO_2 (from environment, ground water, etc.)

Generally, for high quality CAC concrete with w/cm values less than 0.40 and cement contents greater than 675 lb/yd^3 , alkaline hydrolysis is not a concern. Also, it is generally quite rare for significant amounts of free alkalis to be present within high purity CAC concrete. However, if alkalis enter into the concrete and concrete is relatively porous and saturated, damage could occur. This type of attack has not been assessed at the launch complex but as noted this could be one form of deterioration. It should be noted that the refractory castables used in the flame deflectors at KSC specify a maximum water amount per powder ratio (powder is defined as the premixed, packaged dry material) and the amount of cementitious materials in the packaged material is not known. Thus, their resistance to alkali hydrolysis is not known.

2.7 Blended CAC Systems

This review has so far focused solely on concrete containing only CAC as a binder. However, researchers and practitioners in recent years have explored hybrid binder systems, where CAC is blended with other cementitious materials, such as portland cement and calcium sulfates (anhydrite, plaster, or gypsum). Figure 7 shows the common hybrid binders that are used by combining various proportions of the three components (CAC, portland cement [PC], and calcium sulfate) shown in the ternary diagram (after Scrivener 2001).

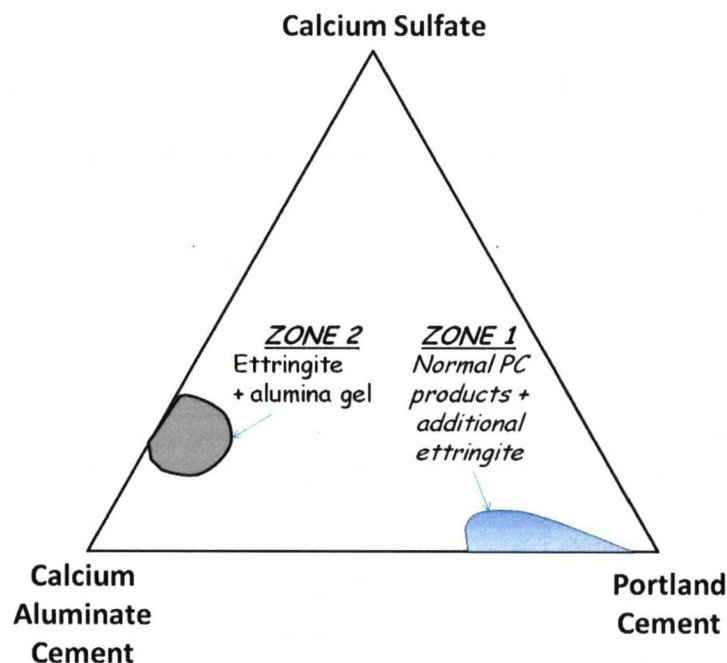


Figure 7 Ternary diagram showing typical formulations based on CAC/PC/calcium sulfate system (after Scrivener 2001)

The combinations shown in Zone 1 in Figure 7 are commonly used in repair applications where rapid setting, hardening, and strength development are desired. Interestingly, the binary mixtures of this type found are used as rapid mortars for use as a “water stops” for stopping leaks (Amatheu et al. 1988).

The combinations shown in Zone 2 in Figure 7, based on mixing CAC with calcium sulfates, produce ettringite as a dominant hydration, along with alumina gel. These mixtures have been used extensively in building chemistry applications, primary for self-leveling floors, which are ubiquitous in Europe. Ettringite has unique properties in that it can be put to use in these applications – it can be used to generate restrained expansion during early hydration, putting the concrete into compression and helping to resist subsequent shrinkage stress. In addition, because ettringite has a high propensity for water absorption, it is useful in floor applications. The mixtures shown in Zone 2 tend to “dry out” faster as ettringite binds free water; this is advantageous as the application of flooring above a cast concrete floor is not allowed until the free moisture inside concrete drops below some specified threshold value. This “dry out” could be advantageous in applications where the refractory material cannot be dried, such as is the case with the refractory material and process currently used for the flame deflectors.

2.8 Applications of CAC Concrete

CAC concrete exhibits several unique characteristics that make it especially suitable for certain specialty applications. The unique properties below are those that make CAC concrete ideal candidates for such specialty applications:

- a. Rapid hardening with initial setting times similar to those of portland cement
- b. Resistance to attack by acids and some other chemicals aggressive to portland cement
- c. Ability to withstand repeated heating to high temperatures
- d. Ability to withstand low temperatures in placing and use
- e. Resistance to abrasion and impact with appropriate aggregates
- e. In mixtures containing portland cement, calcium sulfate, or both, the ability to form ettringite, which can lead to controllable setting and hardening, shrinkage compensation, and combination of free water

The use of CAC for rapid repair and construction applications has gained popularity, especially for pavement, runway repairs, and refractory applications. At NASA it has been used to repair the lining on the flame deflectors. These types of applications typically involve the use of on-site volumetric mixers as the workability and slump retention of such mixtures are generally limited. Some applications in standard ready-mix trucks have been attempted in recent years, where admixtures are used to retard the mixture until it arrives at the job site, where it is dosed with a strong accelerator and potentially additional polycarboxylate-based superplasticizers. However,

this is typically for materials that are cast. Many repair applications use methods similar to shotcrete, referred to as gunning for refractory applications.

CAC concrete can exhibit superior durability when exposed to sulfate and acidic solutions, including sewage pipe applications or acidic environments such as at the launch complex. For sewage applications, this emerging market has allowed for CAC-based products to compete with polymeric pipes. For refractory applications, the resistant to acid attack has made this product a feasible and cost-effective product for aggressive, acidic environments.

CAC concrete has also found considerable use in refractory applications, where CAC cement is required. CAC used for refractory (very high-temperature exposure) applications can have an Al_2O_3 content of 60 to 80 percent, and concrete cast with this cement often contains an aggregate artificially produced from the same binder system, thus creating a composite with very similar thermal and elastic properties, enhancing high-temperature stability and performance. This application is discussed in more detail later. Such mixtures also typically exhibit superior resistance to abrasion and are suitable for applications where abrasion and/or erosion are possible.

2.9 Summary

CAC is an innovative binder that can impart unique properties to cementitious systems. CAC concrete should not be considered as an alternative to portland cement as it is more of a specialized product that is considerably more expensive than portland cement concrete. However, in situations where the unique properties of CAC concrete are desired, such as rapid hardening and strength gain, resistance to sulfates and acids, and excellent resistance to high temperatures, CAC concrete is often the only viable and cost-effective option. When selecting CAC concrete for such unique properties and applications, one should bear in mind the complexities of the system, particularly one should be aware that conversion from metastable hydrates to stable hydrates is thermodynamically favorable and unavoidable. As such, one must design for the converted strength and related properties to ensure that adequate structural performance is realized in the long term.

3 REFRACTORY CONCRETE

3.1 Introduction

Refractory concrete is simply a concrete that is suitable for use at high temperatures. Refractory concrete (or castable) consists of CAC and other materials and are typically premixed combinations of refractory grain, matrix components, bonding agents, and admixtures. A castable is a preproportioned mix of materials packaged and sold for specific application. The vast majority of castables are provided as premixed, bagged products. Trejo and Zidek (2009) recently provided a comprehensive list of castable products with a broad range of characteristics and chemistries for use in various high-temperature applications.

Portland cement concrete has limited applications in high-temperature environments because this material does not retain its integrity when exposed to high temperatures or cyclic temperatures (Guise 1999, Powers-Couche 1992, Gustafero 1983, Neville 1995, Smith 1994). Up to approximately 570 °F, portland cement concrete undergoes normal thermal expansion and loss of

free moisture. In this range some loss of water from the calcium silicate hydrates and the calcium hydroxide occurs. Above 570 °F shrinkage occurs as a result of loss of bound water, with increasing temperatures leading to increased loss of bound water. From approximately 670 °F to 750 °F the calcium hydroxide dehydrates and forms calcium oxide. This process, shown below, is a reversible reaction.



The challenge with the reversible reaction between calcium hydroxide and calcium oxide is that upon rewetting the calcium oxide reacts with the water, resulting in swelling, cracking, and significant strength loss of the concrete. In addition to the issue with the reversible reaction, portland cement is also high in lime and silica, both of which exhibit low melting points.

As the hydration products undergo changes that result in mechanical property loss, the differences in the thermal characteristics of the aggregate and hydrated cement paste can result in further damage. As a concrete is heated, both the cement paste and aggregates expand. At higher temperatures the thermal mismatch between the hydrated cement paste and the aggregate increases, resulting in cracking and decomposition of the hydrated cement paste.

In addition to the decomposition and the thermal mismatch, spalling and cracking during heating are common in concrete exposed to high heat. Vaporization of free moisture occurs at approximately 212 °F, dehydration of the calcium hydroxide at temperatures above 740 °F, and partial volatilization of calcium silicate hydrogels (C-S-H) at approximately 1060 °F are likely responsible for the buildup of internal pressures in the concrete (Montgomery 2003). The vaporization and volatilization are likely the main factors causing internal stress and cracking and spalling of the concrete. It should be noted that significant loss of properties occurs as a result of the decomposition of the calcium silicate hydrate and the calcium hydroxide. Because neither of these products are major components of CAC hydration process, CAC refractory products can exhibit superior performance in high temperature applications.

3.2 Constituent Materials

Refractory concretes include a wide range of constituent materials depending on their application and use. Although a wide range of refractory materials are available, the focus of this report will be placed only on calcium aluminate systems. CAC-based refractory systems have both hydraulic cement and filler materials. Section 2 of this report provided a background on the calcium aluminate hydraulic cement system. Note that various purity levels of CAC are available and that the selection of a particular CAC is primarily based on the service temperature of the environment in which the material is to be used. Although this is the primary selection criteria, it should never be the sole criteria for selecting a CAC system – all critical engineering properties need to be considered.

3.2.1 Background

Aggregates for refractory products are granular materials that have a wide range of service temperatures. Unlike aggregate for conventional portland cement concrete, most aggregates for refractory applications have to be processed. Typical refractory aggregates and their maximum

service temperatures are listed in Table 4. In general, the temperature stability of the aggregate determines the maximum service temperature of the refractory system below approximately 2400 °F. Above 2400 °F the purity of the CAC system has an increasing impact with increasing exposure temperatures. Generally, lower purity binders with proper aggregate are appropriate for service temperatures up to approximately 2700 °F, intermediate binders up to 3000 °F, and high purity binders with appropriate aggregates up to approximately 3400 °F.

3.2.2 Aggregate Gradation

In addition to the maximum service temperature, the aggregate gradation is important in the design and performance of refractory materials. The aggregate system normally consists of between 60 and 85% of the refractory mixture and, as such, can have a significant influence on the performance of the refractory system. Different aggregate gradations result in different cement to aggregate volume ratios, different water requirements, and different workability characteristics of the refractory material. Because poorly graded aggregates require more binder (CAC) and because it is the binder that usually is the constituent that can deteriorate and is the constituent that influences the dimensional stability of the system, using properly graded aggregates is critical. It should be noted that unlike conventional portland cement systems where the aggregate is often perceived as being the inert filler (although in many cases this is not the case) because refractory aggregates are processed, one must consider the thermal properties of the refractory aggregate. In addition, poorly graded refractory aggregates can lead to higher porosities, poor workability, decreased strength, and an inferior final product. Figure 8 shows the service temperature limits of refractory aggregates.

Table 4. Service temperatures of heat-resisting and refractory concretes (Montgomery 2003)

Aggregate Type	Percent Al ₂ O ₃ in CAC	Approximate Service Temperature (°F)
Vermiculite, Perlite, Diatomite, Pumice	39%	1650
Expanded Clay, Expanded Pulverized Fly Ash	39%	2000
Siliceous Sand	39%	650
Limestone	39%	950
Firebrick	39%	2200
Chamotte	39%	2350
Chamotte	50%	2650
Chamotte	70%	2750
Calcined Bauxite	39%	2550
Calcined Bauxite	50%	2750
Calcined Bauxite	70%	3100
White Fused Alumina	70%	3250
White Fused Alumina	80%	3450

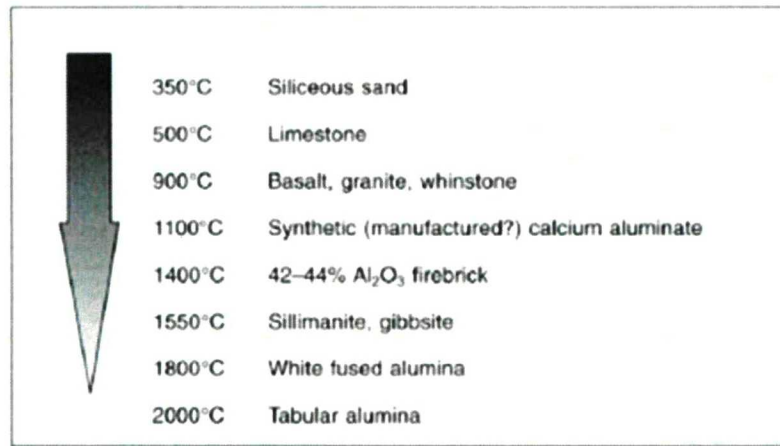


Figure 8 Service temperature limits for various aggregates

Significant work has been performed to optimize the gradation and maximize the packability of constituents in refractory mixtures. Aggregate gradations have been optimized, and significant improvements in the packability of the cement system have occurred over the past 25 years (Stewart 1994, Clavaud et al. 1983, MacZura 1990). This has in large part been accomplished by using dispersing additives and fine particles. Part of the cement system is being replaced by fine particles of similar size, but more significant improvements have occurred by using particle diameters ranging from 4 to 40 mils. By replacing an interstitial void with a particle, the water that used to fill that void is no longer needed, and the overall water content can be reduced. Reducing the water content can improve the performance of refractory systems. However, filling interstitial voids with particles increases the surface area of the constituents, requiring more water to achieve proper workability. Detwiler et al. (1994) reported this same improvement and challenges for conventional concrete materials. Stewart (1994), Clavaud et al. (1983), and MacZura (1990) reported that by optimizing the grading of the particle size distribution in refractories such that the interstices are progressively filled with smaller particles, maximum packing densities can be achieved. The increased water demand can be reduced by using deflocculants and water-reducing agents, which prevent the fine powders from coagulating, providing good dispersion. Good dispersion of the cement and filler particles provides for more homogeneous microstructures and improved strength and durability performance. Increasing the packing density also results in refractory products with higher densities, lower porosities, and better mechanical and abrasion resistance values (MacZura et al. 1984, MacZura 1990, Roy and Hughes 1995). In fact, Reed (1995) reported that the packing density for a monosize system is approximately 62%, and this packing density can be increased to above 75% by adding specific, finer-sized particles that pack the interstices more efficiently.

3.3 Classifications

Alumina and alumina-silicate castable refractories are produced to yield characteristics that meet the application in which the material is placed. Volume stability, modulus of rupture, bulk density, and calcium oxide content are useful measures in distinguishing the characteristics of these materials. As such, the American Society of Testing and Materials (ASTM) classify refractories based on these parameters (ASTM C401, Standard Classification of Alumina and Alumina-Silicate Castable Refractories). This classification is considered by some to be useful

for purchase specifications and quality control. In general, refractories are classified as acid, basic, or neutral. Acid refractories are characterized by high silica contents. Basic refractories generally contain magnesia, lime, or other alkaline earth materials. Neutral refractories consist of refractories that are neither acidic nor basic. However, in many cases there exists no clear distinction between these refractory types. Acid refractories can contain silica, fireclay, zircon, and zirconia; basic refractories typically contain magnesite and/or dolomite; and neutral refractories generally contain high alumina, chrome, carbon, and mullite. This report focuses on alumina-based systems or neutral refractories.

Calcium hydroxide is not formed during the hydration of CAC (see equations 1 through 5). The performance of CAC concrete is dependent on the amount of cement in the mixture or more specifically the amount of calcium oxide in the mixture. The lower the calcium oxide content (and ferrous oxide content) the higher the alumina content. Even though it is the calcium oxide and ferrous oxide content that influences the refractoriness of the material, CAC is often classified by the amount of aluminates that are in the CAC (see Table 2). Higher alumina contents result in lower calcium oxide and ferrous oxide contents. Figure 9 shows the refractoriness of various refractory materials with different compositions (Montgomery 2003). The figure clearly indicates that the higher the alumina and the lower the calcium oxide and ferrous oxide, the higher the refractoriness.

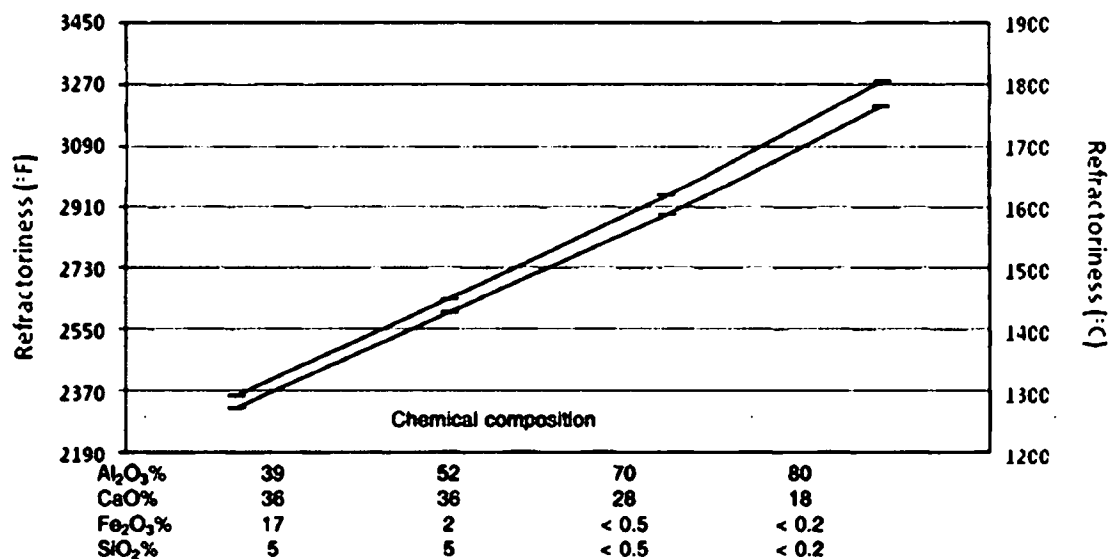


Figure 9 Refractoriness of various chemistries of refractory concrete (Montgomery 2003)

CAC concrete is also classified by the amount of cement in the cementitious system; lower cement contents will have lower CaO contents. As such, classifications for CAC concrete (or refractories) include conventional castables (CC), low-cement castables (LCC), ultralow-cement castables (ULCC), and no-cement castables (NCC). Refractories can also be classified by their density and/or the way they are cast or placed.

Refractories are also classified by the method in which they are placed. Plastic and ramming mixes are products that are tamped or rammed into place. These are typically used for monolithic

placements, for repairs, or for fabricating molded shapes. Plastic mixes typically have higher water contents than ramming mixes and therefore have higher plasticity when placed. Similar to conventional portland cement concrete, higher water contents can lead to higher shrinkage and more cracking. Refractory concrete can also be gunned into place. Table 5 shows the several ways CAC refractories are classified and typical classification limits for these materials.

Table 5. Classification of Refractory Castables (after Krietz 2004)

1. Chemistry and/or mineralogy
a. Alumina content/refractoriness
b. Mineral base
2. Density/thermal insulating value
a. Dense (>120 lb/cf)
b. Medium weight (100 to 120 lb/cf)
c. Light weight (< 100 lb/cf)
3. Cement content (by CaO from cement)
a. Conventional (>2.5% CaO)
b. Low cement (1% < CaO < 2.5%)
c. Ultralow cement (0.2% < CaO < 1%)
d. No-cement (CaO < 0.2%)
4. Flow/placement characteristics
a. Plastic (Vibrated)/Ramming
b. Casting
c. Free-flow
d. Gunning

In addition to the several classifying methods, refractories are also classified by unit weight. As shown in Table 5 refractories exhibiting unit weights of less than 100 lb/cf are considered to be light weight, refractories more than 120 lb/cf are considered dense, and refractories between these weight are considered medium weight refractories.

Refractory concrete materials are resistant to deterioration at high temperatures as a result of the constituent materials (or absence of constituent materials) used to make the refractory and the processes used to condition the material. As far back as 1962 Robson reported that cements with the lowest iron oxide content will produce concretes with higher refractoriness. The iron in the CAC tends to lower the melting point, thereby reducing the refractoriness of the material. However, without proper processing prior to exposure to the high temperature, refractories could perform poorly.

Not all classifications are used for specific mixtures. Typically, only classifications critical to the performance are referenced when classifying refractory materials. This does not mean that refractories are not classified following all classifications – simply that often they are not.

3.4 Proportioning, Mixing, Curing, Drying, and Firing Refractories

Refractory mixtures must resist deterioration in the environment in which they are placed. The development of the bonds that are formed during hydration and processing significantly impact the resistance of these materials. As such, refractory concrete materials fall into three subclasses of service temperature ranges as follows:

- a. Ceramically bonded (materials that have been heated to sufficiently high temperatures, and exposure to these temperatures results in sintering of the various constituents)
- b. heat-resistant concrete
- c. hydraulically bonded (materials that consist of constituent materials that are bonded by the products of the cement and water and typically do not include sintering of the microstructural interfaces)

Ceramically bonded refractories are formed when the cement binder and aggregate particles react thermochemically to form a ceramic bond. The ceramic bond can form as low as 1650 °F but the exact temperature is dependent on the constituent materials. Heat-resistant concretes are concretes that have been dehydrated (dried) but have not yet formed the ceramic bond. This often is the case for refractory materials that have been dried but not yet fired. Refractories with hydraulic bonds typically have not been dried or fired. The refractories currently used in the flame deflectors at KSC are hydraulically bonded refractories (before exposure to the launch environment). These refractories typically exhibit lower performance than heat-resisting concrete and ceramically bonded refractories.

Prior to drying and heating, the refractory constituent materials must be proportioned to meet the in-service requirements. However, unlike conventional portland cement concretes, systematic methods for proportioning refractory concretes are not available. In general, refractory mixtures have an aggregate:cement ratio of approximately 3 to 4:1 by dry bulk volume. Actual ranges can vary from 2:1 to 6:1 depending on the aggregate unit weight and exposure conditions. Within range (that is, in ranges where the cement content is not so high as to cause cracking), increases in cement content will increase most mechanical properties. However, as with conventional portland cement concrete, increases in cement content can result in decreased dimensional stability and eventual cracking of the material. For ceramically bonded refractories, it is recommended that 10 to 15 percent of the aggregate pass the No. 100 sieve (ACI 1979). For most applications trial mixes are required. Because limited standardized procedures are available for proportioning refractories, castables are commonly used as these products are proportioned based on the manufacturer's knowledge of their specific materials.

To achieve the full utility of a refractory, the constituents of the refractory must be mixed well. In addition, all mixing equipment and tools must be well cleaned prior to mixing, especially when these tools have been used for portland cement concrete. As noted earlier, the calcium oxide can reduce the refractoriness of the product but, more importantly, the residual lime, plaster, or cement can induce flash setting of the refractory concrete. Once clean, equipment typically used for conventional portland cement concrete can be used for refractory concrete. The

water content of the mixture will control the strength, dimensional stability, workability, and durability and in most cases should be kept as low as possible (while ensuring sufficient water for hydration). Mixing of materials should continue until the mixture is homogeneous. Care must be taken as some refractories have limited working times, and castables should be placed as soon after mixing as possible.

The period immediately following the placement is termed the curing period for a refractory. The hydraulic bond for most refractories occurs within the first 24 hours and, as such, refractory materials should be cured at least until this time. The objective of the curing process is to maintain sufficient moisture such that the reactions between the CAC and the water can react completely. If curing is not performed, the surface can dry, preventing full hydration in the surface layer. Poorly cured refractories can exhibit dusty and friable surfaces as a result of incomplete hydration. In general, curing should be performed as soon as the refractory sets (often 3 to 4 hours but sometimes up to 10 hours after the addition of water). General methods used for conventional portland cement concrete can be used for refractories. These include using wet mats, plastic sheets, and fogging.

Of particular interest in the curing process is that the curing temperature can have a significant influence on the final strength of the refractory. As discussed in Section 2, the products of the reaction between CAC and water are dependent on the temperature. Thus, the temperature affects the type of hydrate that is formed. If the stable CAH_6 can be formed without having to form the metastable CAH_{10} and/or C_2AH_8 , the increase in porosity from conversion can be avoided. Figure 10 shows the increase in flexural strength of a refractory cured at different temperatures.

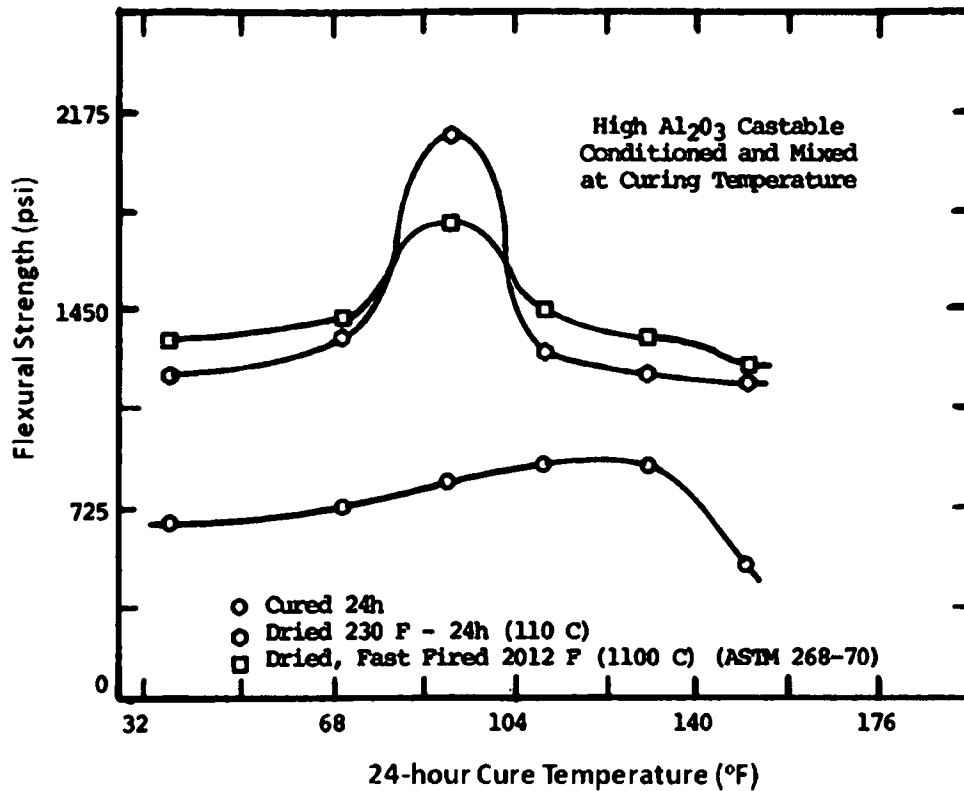


Figure 10 Influence of curing temperature on flexural strength of refractory castable (ACI 547R-79)

After curing there is typically considerable free water in the pores of the freshly-mixed, “green” refractory. If the refractory were exposed to high temperatures without first removing the free water, explosive spalling could occur during firing and/or in-service. To prevent this, refractories are dried before use (and before they are fired). Drying basically consists of removing free water from the pores of the refractory material. To achieve this condition, the refractory specimen should be heated to approximately 200 °F until the free moisture is removed. The drying time depends on the shape and dimensions of the specimen and can be determined by repeatedly weighing the specimen after drying. If the mass of the specimen does not change between drying cycles, the specimen can be considered to be dried, assuming the cycle time is sufficiently long.

The firing process can include several phases. The first firing phase immediately follows the drying phase and can include ramping the temperature from the drying temperature to approximately 685 °F. This firing phase removes the bound water in the hydrated cement paste. Depending on the specimen geometry and dimensions, a typical temperature ramp rate is 90 °F or lower followed by a hold at approximately 900 °F, then a ramp up to the service temperature. Calle et al. (2006) showed that the drying and firing process can have a significant influence on the compressive strength of castable refractory materials as shown in Figure 11. The significant strength loss of Product 1 (Fondu Fyre) may indicate that this product has a high calcium oxide content or is not a refractory material; further studies are needed to determine this. Product 2 (WRP) exhibits continued strength gain on heating and firing, typical of refractory products containing cements with higher alumina contents.

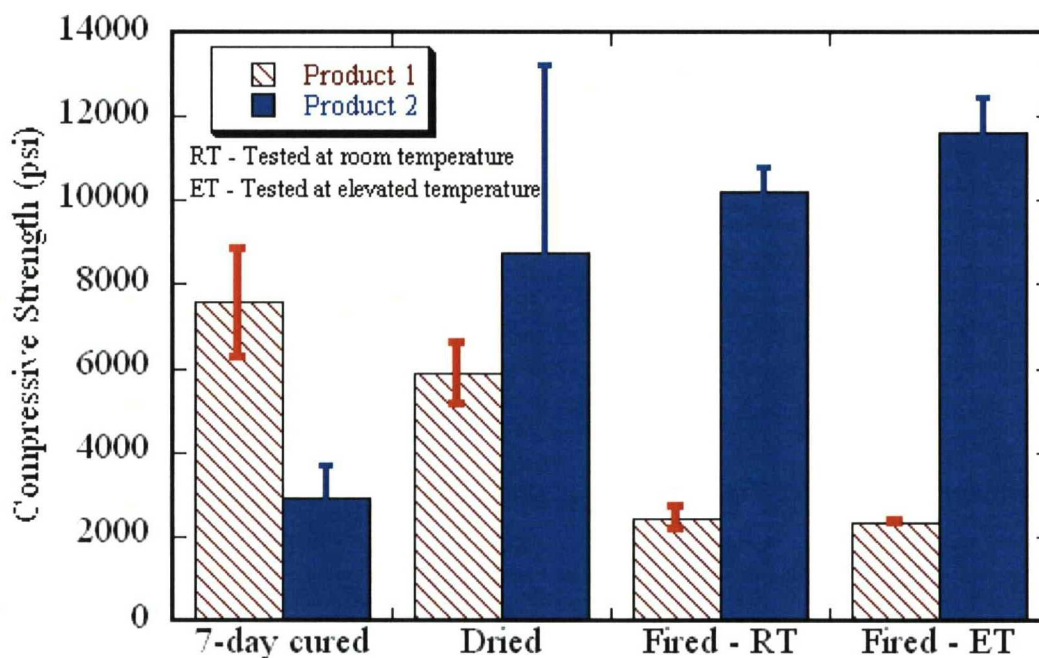


Figure 11 Compressive strength of two castable products as a function of conditioning (after Calle et al. 2006)

One particular challenge at the KSC flame deflectors is the inability to dry and fire the refractory on the flame deflector. From Figure 11 it can be seen that the strength of a fired refractory can increase by over 300% after the refractory material has been conditioned (dried and fired). However, the large surface area of the flame deflector and the exposure to the elements would make drying and firing unfeasible (although some communications indicate that drying and firing of refractories with large surface areas may be occurring in Japan). Because drying and firing is not being performed at the launch complexes, fibers that melt on heating are added to the refractory. This allows the internal water to escape once the fibers melt, possibly preventing explosive spalls. However, adding the fibers does not increase the strength and performance of the refractory, and the full value of the refractory system is not being realized.

3.5 Summary

Using a refractory product that can be cured, dried, and fired could provide significant improvements in the performance of the refractory linings in the flame deflectors. As already noted, one objective of this report is to develop a system of prefabricated refractory panels that can be fabricated, transported, and installed in the flame deflectors. These panels would be conditioned (dried and fired) prior to being transported and should exhibit significant improvements in performance. However, no system comes without challenges. A prefabricated panel system will have joints, and inspections of the flame deflectors has indicated that cracks (uncontrolled joints) exhibit higher erosion and abrasion rates. In addition to this potential challenge, the design, fabrication, transportation, and constructability plan for the panel systems would have to be developed and followed in the field.

4 LAUNCH COMPLEXES AT KENNEDY SPACE CENTER

4.1 Introduction

As shown in Figure 12 the launch complexes at KSC are located within 1000 feet of the Atlantic Coast (<http://corrosion.ksc.nasa.gov/index.htm>; accessed April 1, 2009). In addition to the severe exposure conditions of the launches, the launch complexes are subjected to the highest corrosion rates in the United States (<http://corrosion.ksc.nasa.gov/>, accessed December 7, 2008). Both the launch and natural environments are severe, and the durability of the launch complex and the safety of the launch crew and vehicle require that high-performing materials be used at the launch complexes. However, to determine the characteristics of the materials needed for high performance, details of the structure and the environment should be defined. The following discussion will provide information on the design and construction of the launch facilities at KSC and will provide a general overview of the launch and natural environments. This information can then be used to define material characteristics for the proposed prefabricated lining panels.

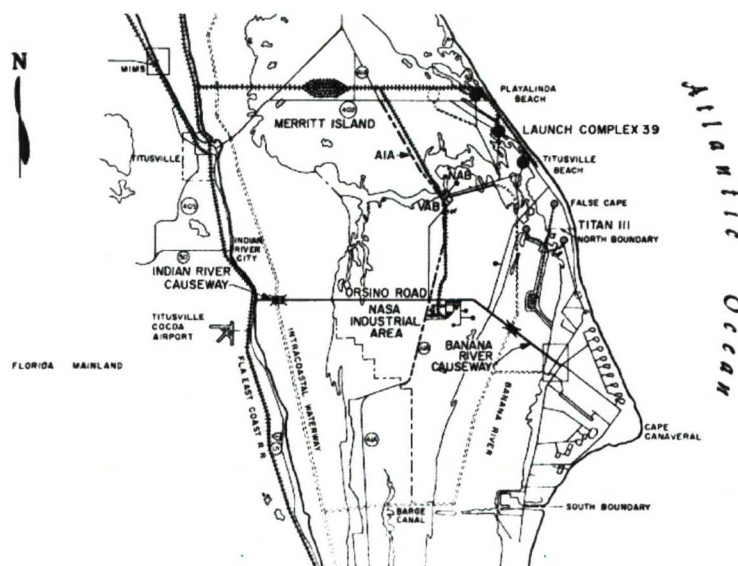


Figure 12 Site plan of Launch Complex 39 in 1963 (<http://en.wikipedia.org>, accessed March 3, 2009)

4.2 Exposure Environments at the KSC Launch Complexes

The environment at the KSC launch complexes presents several challenges for structures. First, the salt water exposure from the Atlantic Ocean presents significant corrosion challenges. Second, the environment during launching of space vehicles presents a short, but very severe and caustic environment. Optimizing materials and systems is essential to minimize the life-cycle costs for the launch complexes.

4.2.1 Florida Coast Environment

KSCs launch facilities are located within 1000 feet of the Atlantic Ocean and the salt, or more specifically the chlorides, from the ocean can result in accelerated and localized corrosion.

Coburn (1978) reported a mean corrosion rate at KSC of carbon steels was 42 mils per year, over twice as much as the next highest corrosion rate observed in the US. The mean precipitation for Titusville, Florida, is 52.79 inches, and the low, mean, and monthly precipitation is shown in Figure 13. The mean temperature for the area is 72.2 °F. Figure 14 shows the monthly mean values (mean low, mean, mean high). The area has a relatively high mean temperature, relatively high precipitation, and is located next the Atlantic Ocean where chlorides are prevalent. The environment should be considered very aggressive for corrosion conditions.

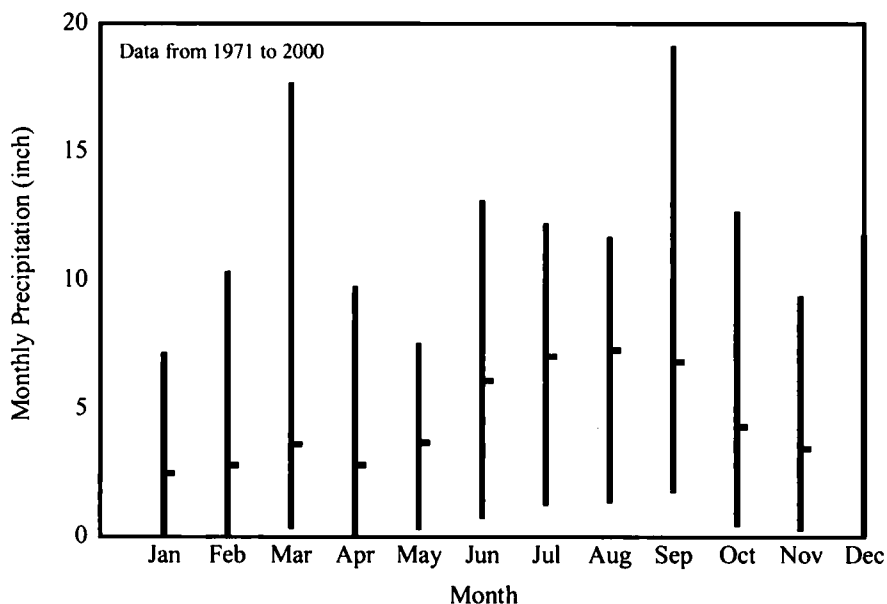


Figure 13 Monthly precipitation (low, mean, high) near KSC (Titusville, Florida) (NOAA 2008)

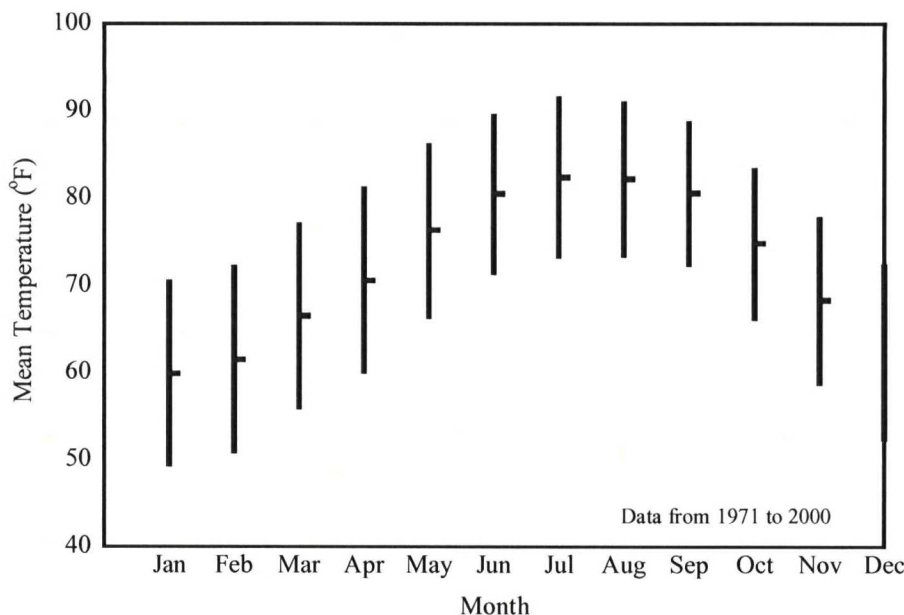


Figure 14 Mean monthly temperatures near KSC (Titusville, Florida) (NOAA 2008) Launch Environment

4.2.2 Launch Environment

During vehicle launches the flame deflectors are exposed to severe environments. Two solid rocket boosters provide the main thrust to lift the Space Shuttle into space. Each SRB has a thrust of approximately 3,300,000 pounds at launch and provides 71.4 percent of the thrust at lift-off and during the first-stage ascent. The SRBs are the largest solid-propellant motors ever flown, and each is approximately 149 feet long and 12 feet in diameter (see Figure 15). The propellant in each SRB consists of an ammonium perchlorate (oxidizer, 69.6 percent by weight), aluminum (fuel, 16 percent), iron oxide (a catalyst, 0.4 percent), a polymer (a binder that holds the mixture together, 12.04 percent), and an epoxy curing agent (1.96 percent). The ammonium perchlorate oxidizer decomposes into nitrogen, water, oxygen, and hydrogen chloride. The hydrogen chloride becomes hydrochloric acid when dissolved in water. The polymers and curing agents (generally CH_2) burns with some of the oxygen to produce CO_2 and water. The powdered aluminum burns with oxygen to produce Al_2O_3 .

(<http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/srb.html>, accessed June 12, 2008).

Refractory materials can hold up well in acidic environments; however, testing is required to confirm this. No requirements for acid resistance are provided in the current KSC specifications for refractory materials (specifications are presented later), and the influence of the acid exposure on the performance of the refractory is not known. In addition to the severe acidic exposure, the launch imposes loads on the flame deflectors. KSC-STD-Z-0012B, Flame Deflector Design, Standard for, provides a method to assess the loading on the SRB exhaust impingement area, but limited information on the design assumptions were available and the design loads could not be determined. The SRBs also expose the flame deflectors to high temperatures – the SRB side is exposed to temperatures as high as 3000 °F for up to 10 seconds during the launch. Thermal loads in the deflector can be high. A methodology for assessing the thermal loads during a launch is also provided in KSC-STD-Z-0012B.



Figure 15 **Photograph showing SRBs on launch pad**

4.3 Structures

A schematic of the flame deflector systems for LC-39 (A and B) is shown in Figure 16. Figure 17 shows a photograph of the SRB side of the flame trench. Flames, exhaust, and loosened materials are channeled through these trenches with the objective of preventing them from bouncing back and hitting the launch complex and space vehicle. The flame trench is 490 ft long, 58 ft wide, and 40 ft high. One side of the system was designed to deflect the flames and exhaust from the vehicle's main engines (the left side in Figure 16), while the other side was designed to deflect the flames and exhaust from the two SRBs (the right side in Figure 16). The SRBs burn at approximately 3000 °F while the main engines burn at lower temperatures. The higher temperatures of the SRB exhaust lead to more severe launch exposure conditions, resulting in more damage to the deflector unit on this side. The ability to safely meet the requirements of diverting the flames, exhaust, and other small items loosened during a launch is dependent on the

integrity and performance of the refractory system used in these deflector units. Because the current refractory materials cannot be dried or fired, an alternative lining system consisting of prefabricated panels has been proposed.

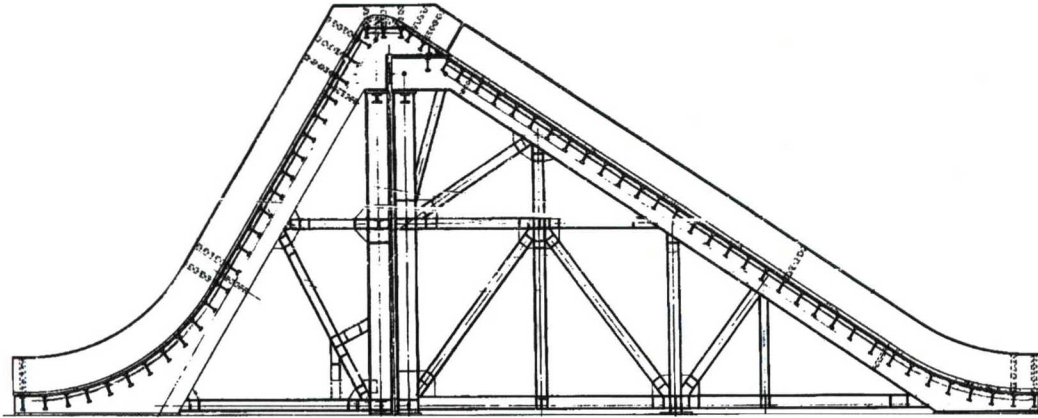


Figure 16 **Side elevation view of flame deflector**



Figure 17 **Photograph of SRB side of flame deflector**

The flame deflectors consist of steel base truss structures. These steel truss systems support a steel base plate that is protected with the refractory linings. The base structures have been repaired and rehabilitated several times as a result of corrosion. A recent report to NASA estimated the average annual direct cost to repair the steel structure is approximately \$420,000 (Trejo et al. 2009). Figure 18 shows photographs of the underside of the flame deflector's base structure and an example of corroded steel members. The analysis of the performance of the steel base structure is beyond the scope of this report but it should be noted that the integrity and stiffness of the steel base structure can influence the performance of the refractory lining. As the structure corrodes, the stiffness can decrease, leading to more deflections during launches, which can result in increased cracking of the refractory lining.



**Figure 18 Underside of steel base structure of flame deflector (left);
close-up of corroded steel framing (right)**

The lining consists of a castable refractory material that was approved for use over 50 years ago. It should be noted that this refractory is the only refractory material approved for use as a lining material on the flame deflectors at KSC. The castable refractory is gunned onto the steel base structure where an expanded steel mesh and studs are welded to the steel base plate to achieve composite action with the refractory lining. Figure 19 shows the steel mesh after failure of the refractory cover. Figure 20 shows the exposed tops of the studs after abrasion of the refractory lining.



Figure 19 Exposed steel mesh after launch



Figure 20 Exposed tops of studs (some studs circled for clarity) after launch

The refractory lining undergoes continual repair. Trejo et al. (2009) provided an analysis of the damaged area and Table 6 shows the reported values as a function of launch date for both launch complexes. On many occasions the quantity of damage was not reported, and the actual damage was significantly higher than the reported damage. The authors reported that for Launch Complex 39A the amount of damage increases nonlinearly as a function of time (a quadratic function to the second power was used to estimate the amount of damage). For Launch Complex 39B, the authors reported that the damage increased linearly as a function of time.

In general, the refractory linings exhibit significant damage, and the efforts and costs required to repair these damaged areas are significant. Significant planning is also required for the repair of the refractory lining. In addition, cracks and spalls in the lining leave the base structure exposed to the aggressive Florida environment and the aggressive launch environments. These cracks and spalls likely increase the rate of deterioration of the steel base structure and other auxiliary equipment housed below the flame deflectors (referred to as the catacombs).

Table 6. Reported repair quantities for refractory lining

No.	Launch Complex 39A		Launch Complex 39B	
	Date of Launch	Area of Damage (sq. ft.)	Date of Launch	Area of Damage (sq. ft.)
1	4/12/1981	41	1/28/1986	238
2	8/2/1991	1645	10/6/1990	375
3	9/12/1991	120	12/2/1990	720
4	11/24/1991	362	4/5/1991	225
5	1/22/1992	530	7/31/1992	30
6	3/24/1992	330	4/8/1993	55
7	4/26/1993	209	6/21/1993	50
8	2/3/1994	40	9/12/1993	70
9	7/8/1994	570	10/18/1993	100
10	3/2/1995	246	3/4/1994	355
11	2/11/1997	5	9/9/1994	245
12	7/1/1997	10	6/20/1996	90
13	8/7/1997	21	11/19/1997	9
14	9/25/1997	125	10/29/1998	75
15	1/22/1998	12		
16	5/31/2008	2000		
Sum		6266	Sum	2637
Average		392	Average	188

4.4 Summary

An alternative system could reduce the significant efforts and costs associated with the repair and rehabilitation of the flame deflectors. Although fibers are mixed into the castable refractory lining on the flame deflector and this can prevent explosive spalling, the full benefits of a good quality lining system are likely not being realized. A system in which the refractory materials can be dried and heated may improve the performance of the refractory lining system, thereby reducing the time, effort, and significant costs associated with repairing and rehabilitating the flame deflectors at KSC.

5 REFRACTORY CONCRETE REQUIREMENTS AND PROPERTIES

5.1 Introduction

Reports indicate that the current refractory material used in the flame deflector at KSC was formulated in 1959. This is the only refractory material approved for use in the flame deflectors. Because the product was last approved in 1966 and because “qualification” procedures are not well defined and very difficult to “pass,” the manufacturer is obligated to continue to use the 1959 material. This section provides a review of the current specifications for refractory materials used at KSC and presents a range of properties available from commercially available refractory products. The objective of this section is to simply show that other products may be available for improved performance in the flame deflector. This summary is not intended to be a comprehensive analysis of material performance and should only be used as a guide to identify potential materials that may provide improved performance – testing of these materials will be required. Also, it is not known if commercially available refractories can meet all exposure requirements of the flame deflectors. A current research program is underway at NASA to determine this, and a new material may be needed.

To assess the properties of a limited number of refractory products, a small test program was performed as part of this contract. Data from these tests are provided.

5.2 KSC Refractory Requirements

The most recent KSC specification for refractory concrete (KSC-SPEC-P-0012) was published on April 25, 1979 (see Appendix B for specification). A new specification is currently being considered. The 1979 specification provides requirements for refractory concretes used for heat and blast protection of the flame deflector units and surrounding areas. The general requirements include a qualification process, required material characteristics, and minimum fresh- and hardened-material requirements. Quality assurance provisions and material packing requirements are also provided in the specification.

The quality assurance section provides information on how manufacturers could qualify their products for use at KSC. The general process includes making test specimens and exposing these specimens to an actual launch environment. Requirements for the acceptance of refractory concrete materials used at KSC include the following:

- shall have a 7-day compressive strength of 4,500 psi,
- shall have a 24-hour strength of at least 90 percent of the 7-day strength,
- shall be workable when placed,
- shall resist degradation of thermal-protection characteristics caused by seacoast exposure,
- shall not crack or spall after exposure to a launch environment,
- shall not “erode” more than 1/8 inch after exposure to a launch environment, and

- shall have a maximum heat flux of 3,300 Btu/ft²-sec.

Several test programs were performed to assess potential refractory lining products. In 1966 five refractory products were assessed. These included Fondy Fyre WA-1, Fondy Fyre XB-1, portland cement concrete, H-E Harcast ES, and H-W Special Mix 13-65. KSC-DF-3735 (Flame Deflector System Repair Launch Pad 39A and 39B, Kennedy Space Center, Florida), Solid Propellant Rocket Exhaust Effects (Spree) and Methods of Attenuation (Vol. 2, Part 2, 1966), reported that “Fondy-Fyre WA-1 was selected as the best all around coating for large-scale applications.” Further testing was conducted to investigate the performance of more refractory materials from approximately 1981 to 1993. The objective of this test program was to potentially qualify alternative materials for use in and around the launch complexes at KSC. Although the Fondy Fyre material was deemed as the “best all around coating,” it did not pass the requirements in the 1981 to 1993 testing program. Because no other refractory products were qualified, the product continued to be used in the flame deflectors. In a small study in 2006, Calle et al. showed that the qualified material exhibited lower mechanical property characteristics than other tested products. However, the process of qualifying materials is extensive and unreliable, and it was recommended that an alternative approach be used to qualify materials.

In addition to the issues with the qualifying procedure, several limitations in the existing KSC specifications (KSC-SPEC-P-0012) have been identified. These include the following (after Trejo and Calle 2004):

- a. Requirements for the evaluation of specimens require that the manufacturer provide samples to KSC for testing. These samples are likely cast, dried, and fired, as is common with refractory products. However, refractory concrete in the flame deflector units typically is not exposed to any curing regime, to drying, or to firing. Performance of the tested samples and as-placed materials likely vary significantly.
- b. Key performance parameters, such as the refractory’s propensity to crack, are not included.
- c. No guidance or requirements on material storage are provided. CAC can hydrate with time under storage conditions that can significantly change the performance of the material.
- d. No guidance or requirements are provided on placement procedures, curing, or other critical construction practices required for long-term performance.
- e. No methodology is provided for qualifying materials.

Regarding (a) in the above list, as shown in Figure 11, significant differences can be obtained from processing of the refractory materials. These improvements cannot be realized if the refractory cannot be dried and fired. The importance of curing, drying, and firing should be defined in the specifications. In addition to the conditioning requirements of the refractories, the specifications are silent on the placement or qualification of the materials. Improperly placed

refractories can negate all improvements and advantages of properly designed and proportioned refractories.

As important as the material characteristics and construction methods are to produce a durable lining, the qualification process is as important to achieving a high quality product. A transparent process that requires producers or suppliers (or teams thereof) to proportion, mix, place, cure, and process should be developed. The process should include that the manufacturer first provide statistically valid data to NASA, following all the requirements for all critical refractory characteristics. If the refractory characteristics are found to meet these requirements, the producer, supplier, or team should provide NASA with samples, produced in the same manner as the samples in which the data were provided, for all pertinent refractory characteristics. NASA personnel can then perform testing and perform a statistical comparison of the producer's (or supplier's) data and the data obtained from the NASA testing. If the data are statistically validated by NASA, the producer, supplier, or team can then provide NASA personnel with unhydrated material (e.g., castables) such that NASA can perform further validation of the materials and their properties, if desired. Also, results from placing test panels in the flame deflector during launches are likely not repeatable, and consideration should be given to designing and constructing an economical test facility for evaluating the refractory products. As noted, the placement technique can significantly influence the performance of the refractory product and sample fabrication methods should mimic field application techniques.

Trejo and Zidek (2009) provided a significant list (over 800 products) of available refractory products and recommended several potential products for testing. The authors ranked refractory materials based on linear length change, cold modulus of rupture, hot modulus of rupture, thermal conductivity, cold crushing strength, and manufacturers reported recommended service temperature. The analysis identified 7 potentially "best" products for potential further investigation. However, several more products that could meet the exposure conditions and performance requirements of the flame deflectors should be considered. Table 7 shows the products recommended for further testing.

Table 7. Products identified for possible future assessment for potential use in flame deflectors (after Trejo and Zidek 2009)

Rank	Product	Application Process	Length Change (%)	Cold Module of Rupture (MOR) (psi)	Hot MOR (psi)	Thermal Conductivity (Btu-in/h-ft ² -F)
1	Kaolite 2300-LI	Castable	-0.1	160	NA	NA
	Kaolite 2500-EXHS	Gunning	-0.1	500	NA	NA
2	ANH HP Cast Maxima	Castable	0	1800	NA	NA
	ANH NARCO Guncrete AR	Gunning	0	1500	NA	NA

3	Surgun T-9	Gunning	0	1120	NA	NA
4	ANH Greenlite Castable 22	Gunning	0	300	NA	NA
5	Resco Products, Inc. Progun 30	Gunning	0.05	850	NA	8.6

5.3 Properties of Refractory Concretes

5.3.1 Typical Values from Commercially Available Products

A wide range of refractory products are commercially available, and the properties of these products exhibit a wide range of values. To provide a sense of the potential limits of the properties, a summary of data on specific material properties is provided. By summarizing the data, designers will have a sense of the material properties available to design the protective lining system. A monolithic lining system and a panel system can be constructed, both have advantages and disadvantages. By providing a general range of material properties, designers can better optimize these designs. Table 8 shows the range of properties and characteristics of commercially available refractory products.

Table 8. Range of properties for commercially available refractory products

Characteristic	Approximate Low Value	Approximate Mean Value	Approximate High Value
Service Temperature (°F)	1000	2500	3500
Cold Compressive Strength (psi)			
After Drying	100	6600	>20,000 ^a
After 1000 °F	100	7100	>20,000 ^a
After 1400 °F	100	6300	>20,000 ^a
After 1832 °F	70	7200	>20,000 ^a
After 2300 °F	450	8800	>20,000 ^a
After 2700 °F ^b	150	15,500	>20,000 ^a
Cold Modulus of Rupture (psi)			
After Drying	40	1500	3500
After 1000 °F	40	1500	6000
After 1450 °F	20	1500	6000
After 1832 °F	40	1800	7000
After 2300 °F	190	2200	7000
After 2700 °F ^b	190	2700	>10,000
Permanent Change in Length (%)			
After Drying	-0.1	0.08	0.6
After 1450 °F	-1	0.18	1.8
After 1832 °F	-1.5	0.25	2
After 2300 °F	-1.5	0.48	4
After 2700 °F (or maximum service temperature)	-0.3	>1	>5

Thermal Conductivity (BTU-in/hr-ft ² -F)			
@ 230 °F	1.7	18	50
@ 500 °F	0.8	6.5	30
@ 1000 °F	1.0	8.5	70
@ 1500 °F	1.1	15.5	>100
@ 2000 °F	0.9	24.5	>100
@ 2500 °F	4.6	24.5	>100
@ 3000 °F	9.1	35.5	>100
a. Specialty products			

5.3.2 Results from Limited Test Program

Several refractory castables and CAC cements were tested for strength, setting time, and flow as part of this contract. Strength specimens were testing after a 24-hour cure, after a 24-hour drying period, and after firing. The objective of this testing was not to perform a comprehensive study of these properties but was instead to determine if “typical” commercially available products fall within the typical ranges reported in Table 8. The flow and setting time were assessed because this information is not readily available from the manufacturers and these characteristics could be critical for the constructability of prefabricated panels. Products evaluated included Cercast HT and Cercast 2900 (Vesuvius), and R Max C, Rescicast 17EC, and Purotab (Resco Products Inc.). Four Secar cements made by Kerneos were also evaluated, including Secar 41, 51, 71, and 80.

The target w/c for the Secar mixtures was 0.3. Instead of targeting a w/c, the castables were batched and mixed to meet a target flow of 25%. However, values ranged from approximately 10 to 50%, with the exception of the R Max C, which was sensitive to the water content and higher flow values were achieved. Mixing was performed in accordance with the procedure outlined in ASTM C305-99, Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. Modifications to the mixing times occurred when the mixture was obviously not mixed to a homogeneous state. For instance, if larger batches were mixed, the mixing time was increased to 4 minutes with a short interval in the middle to scrape the edges of the mixing bowl. Also, mixing time was increased when water or material was added in order to change consistency.

Flow testing followed the procedures outlined in ASTM C1445, Standard Test Method for Measuring Consistency of Castable Refractory Using a Flow Table. Values are reported in mean percent increase in flow.

Assessment of the setting time was performed according to ASTM C191, Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle, using the manual method. The CAC cement mixes were testing according to the standard. However, for the castables the aggregate was first sieved from the mixture, and the test was performed on the remaining powder. The authors are aware that this could change the set time for the mixtures but found this necessary as the needle on the testing apparatus tended to not penetrate the castables with larger aggregates resulting in apparently false short set times.

Initial setting times for the CAC ranged from 3 hours and 15 minutes to over 9 hours. Final set times for these mixtures were in all cases within 1 hour after the initial set time. Setting times for the castables was considerably lower – from 1 hour and 45 minutes to 5 hours and 15 minutes. As with the CAC mixtures, all final set times were within 1 hour of the initial set time. Although setting time is not a direct measurement of the time to work the material, the longer set times are an indication that refractory materials can be workable for longer periods. This may be necessary for constructability issues with the prefabricated panel system.

Compressive strength samples were tested in accordance with ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) and ASTM C133, Standard Test Methods for Cold Crushing Strength and Modulus of Rupture of Refractories. The cured samples were tested following ASTM C109, and the dried and fired samples were tested following ASTM C133. Specimens were fired for approximately 9 hours between 1000 °F and 1500°F.

Figure 21 shows the data from the compressive strength testing of the CAC. With the exception of the Secar 41, all mixes that were dried exhibited increases in strength. The firing of the samples did not result in increased strength, and this is likely due to the lower firing temperature. A higher firing temperature would have likely led to increased strengths due to the formation of the ceramic bond. More importantly, the strength values ranged from approximately 4000 to 9000 psi, values well within the ranges shown in Table 8.

Figure 22 shows the compressive strength values from the refractory castables tested in the program. Only the Cercast 2900 and the Purotab showed increasing strength with drying and firing, and the Purotab showed significant increases in the strength with successive processing. Because the manufacturers do not provide information on the castable constituents or the proportions, it is difficult to determine why the mixtures performed in the manners shown. This was not the objective of this testing. The tested values fall well within the ranges shown in Table 8.

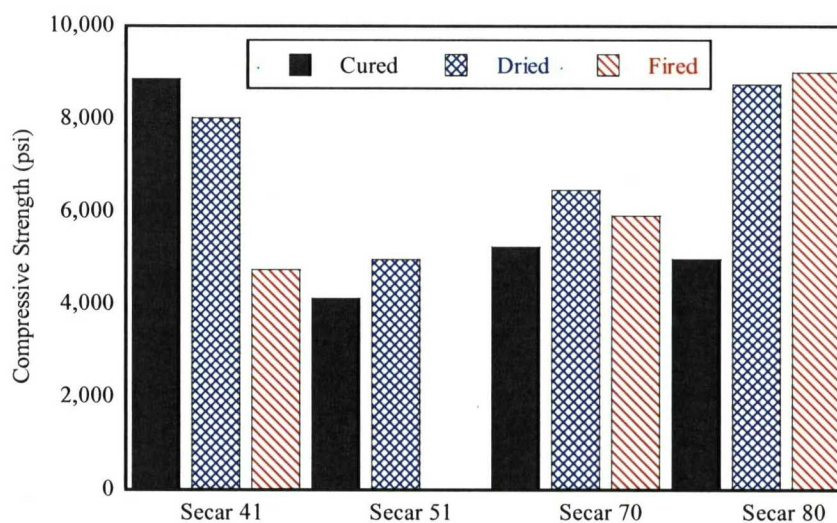


Figure 21 Compressive strength values for CAC cements

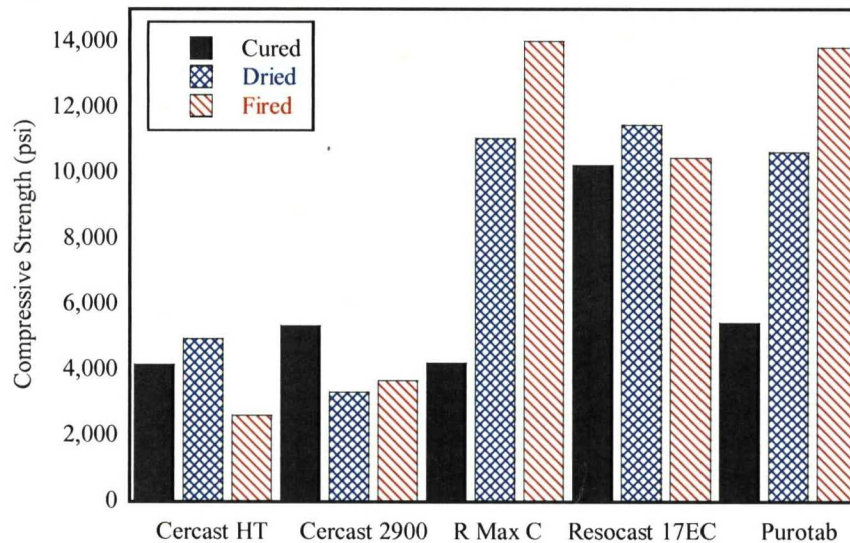


Figure 22 Compressive strength data for cured, dried, and fired castables

5.4 Summary

This section provided a review of the current KSC specifications for refractory concrete, provided a general overview of properties of commercially available refractory products, and provided limited data from a small testing program. The mean values of the mechanical properties from the available products (values provided by the manufacturers or suppliers) can far exceed the NASA requirements. To confirm that these properties were achievable, a small testing program was performed. The results from the testing program confirm that improved characteristics are achievable in the lab. Although field installation could reduce the material properties, sound field practices should result in better performing refractories when compared to the currently used refractory. Whether these characteristics are sufficient to resist damage and FODs is unknown, and this is the focus of a current research program at NASA. The general ranges of properties will be used to provide a conceptual design of prefabricated, precast panels.

6 CONCEPTUAL DESIGN OF A PREFABRICATED PANEL SYSTEM FOR THE FLAME DEFLECTOR

6.1 Introduction

The previous sections presented challenges associated with the materials used in the flame deflectors at KSC. This section will present challenges associated with the current design and will present a new concept of lining the flame deflector with a series of prefabricated refractory panels. A preliminary design will be presented to determine if this proposed system is feasible. A general overview of the constructability plan will also be presented.

6.1.1 Challenges Associated With the Current Refractory Lining

The lining of the flame deflector is exposed to aggressive environments and undergoes significant damage during launches. Figure 23 shows typical damage that occurs after launches. One observation of the author and other inspectors was that the refractory lining exhibits increased erosion/abrasion during a launch at cracked areas in the refractory lining. In addition, cracks tend to be in locations where exhaust can penetrate the lining, and this can lead to further cracking, spalling, and eventual FOD. Eliminating or minimizing cracking would likely result in significant reductions in damage to the lining.

The flame deflector is approximately 58 feet wide by 68 feet long. The refractory lining for the flame deflector is composed of a monolithic mass of refractory concrete placed using gunning procedures. In concrete technology the maximum spacing of control joints, used for controlling cracking, is approximately 24 to 30 times the thickness of the slab, depending on the maximum size of the aggregate in the concrete. For the lining on the flame deflector, the maximum joint spacing would be approximately 12 feet. The width of the deflector is almost 5 times this distance. As a result of this, cracking of the refractory lining would be expected. Figure 24 shows examples of erosion at cracks and cold joints. Figure 25 shows an example of FOD that occurred during a launch in 2007. A reasonable approach in the design of the refractory lining system that reduces cracking and the resulting damage of the lining is needed.



Figure 23 Typical damage in the flame deflector after a launch

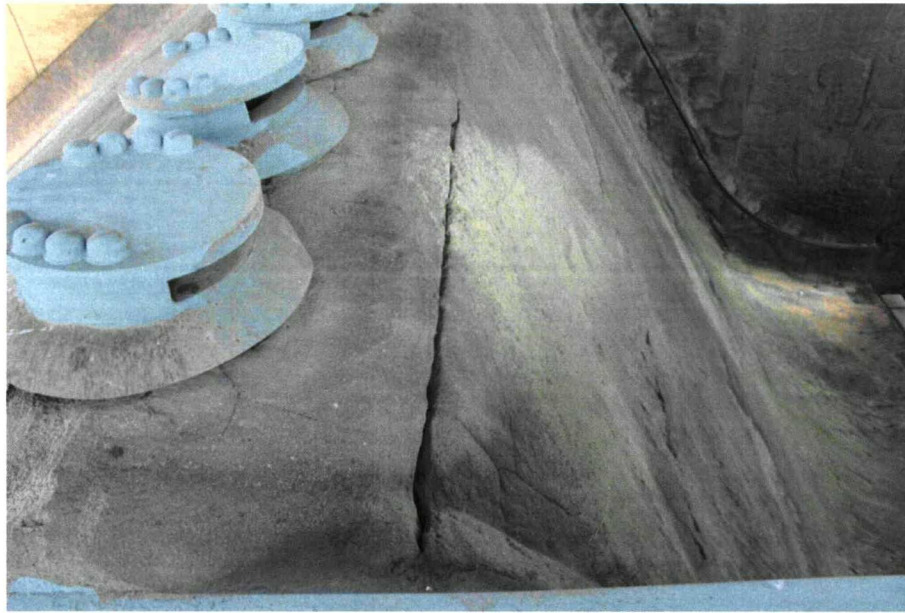


Figure 24 Photographs showing erosion abrasion at crack areas



Figure 25 FOD located outside of the flame trench

6.1.2 Design Options for the Refractory Lining System

Several options exist for constructing the refractory lining system. The general methodology should minimize the potential for uncontrolled cracks, minimize unreinforced and open joints, and use refractory materials that exhibit high mechanical properties, good durability, and good dimensional stability. The refractory material requirement lends itself to using refractory materials that can be cast, cured, dried, and fired and will necessitate the need for a prefabricated panel system.

One option to minimize the formation of cracks is to provide joints in the refractory linings. However, unreinforced and open joints will behave similar to a crack, exhibiting significant abrasion and/or erosion. An unreinforced, open joint would also allow for the exhaust gases to penetrate the joint, possibly imposing an uplift force resulting in failure of the lining and FOD.

Another option for controlling cracking is to avoid joints and provide conventional reinforcement in refractory concrete lining. This option would likely require large reinforcement ratios (i.e., the ratio between the cross-sectional areas of steel and concrete) and could present constructability challenges with placing reinforcing bars on the sloped deflector face. If conventionally reinforced panels could be prefabricated and placed on the deflector's face, the constructability

issue could be resolved. However, the joints would still be open and would necessitate the need for a "closure pour." A closure pour is when cast in place (CIP) material is placed between prefabricated systems to close the opening between the systems. This would significantly increase the interfaces between the prefabricated panels and the CIP material, increasing the probability of damage, cracking, and FOD.

The amount of steel reinforcement required for the prefabricated panels can be reduced by using prestressed refractory concrete panels. This method is common in bridge construction and has been very successful in reducing costs. However, using prestressed panels does not address the challenge of having a large number of closure pours.

The development of a lining system with conventionally reinforced panels that can be post-tensioned seems to be a viable option. This system can minimize panel-CIP interfaces, can provide a compression force across the panel interfaces, can provide a strong panel, and, because the panels can be prefabricated in a controlled environment (i.e., panels can be cured, dried, and fired), will provide a lining system with high durability and dimensional stability. With this system the formation of cracks can be minimized by keeping a sufficiently small panel size, and the corrosion-induced deterioration can be minimized by keeping the reinforcement and posttensioning strands sufficiently below the concrete surface. With this system the joints between the panels can be filled with refractory grouts and then compressed, thereby preventing the penetration of the exhaust and minimizing the chance of panel failure and FOD.

Table 9 shows the summary of the potential systems for construction of the refractory lining system on the flame deflector. The development of a refractory lining system consisting of prefabricated, conventionally reinforced panels that will be posttensioned together seems to be the best viable option. As such, the following work will focus on the development and feasibility assessment of this system.

Table 9. Comparison of the potential damage levels associated with various design options

Floor system	Potential damage level due to:			Potential Constructability
	the presence of open cracks	the presence of open joints	the cracking induced by high temperature corrosion	
Current CIP refractory system	High	High	High	Good
Conventionally reinforced panels	Low, if reinforcement ratio is large	High	High	Good
Pretensioned panels	Low	High	Low	Good
Posttensioned, conventionally reinforced panels	Low	Low	Low	Good

6.2 The Proposed Posttensioned Liner System

Some important definitions used in this conceptual design are as follows:

- Refractory Concrete Panel (RCP) – A prefabricated, conventionally reinforced panel made with refractory material
- Posttensioned Liner (PTL) – A set of 3 or 4 RCPs aligned in a horizontal row on the deflector and posttensioned in the direction perpendicular to the flame deflector walls
- Refractory Concrete Closure-Pour Panel (RCCP) – A conventionally reinforced, cast-in-place RCP used in the closure-pour between the two adjacent posttensioned (PT) liners in the same row.
- Posttensioned (PT) Liner System – The complete set of PT liners and RCCP that form the entire liner for the flame deflectors. Figure 26 shows the plan view and placement pattern of the entire PT Liner System.
- Steel Base – The existing thick steel plate (supported by a steel frame) designed to resist the high pressure exhaust air from the solid rocket booster (SRB) engines.

The proposed PT Liner System design will consist of RCPs that are 8 ft x 8 ft x 0.5 ft in dimension (or approximately this dimension as the exact dimensions of the deflectors will dictate these dimensions). The RCPs will be posttensioned after being placed on the steel base to form PT Liners. In Figure 26, the left-to-right direction will be defined here as the X-X direction, and the axis perpendicular to the X-X direction (up and down the deflector) will be defined as the Y-Y direction. The shaded cells in Figure 26 indicate the RCCP.

The main design philosophy is to install and secure the RCPs adjacent to the walls (1x1, 1x8, 2x1, 2x9, etc). After these panels have been properly secured to the steel base (via welding), the adjacent panels in the X-X direction will be placed and posttensioned to these secured panels. The closure pours will then be cast with refractory materials, thereby significantly reducing the amount of undried, unfired panels in the deflector. Although joints will exist, these joints will be held together with the posttensioning strands and thus are considered to be closed joints. To ensure a good fit, it is anticipated that the panels will be fabricated using a match cast system, and refractory grouts will be placed between these panels prior to posttensioning to fill any minor voids. Refractory grout will also be required for the bedding of the RCPs. For the system to be successful, the RCPs must match the curvature of the deflector, and surveying will be needed to determine this curvature of the RCPs.

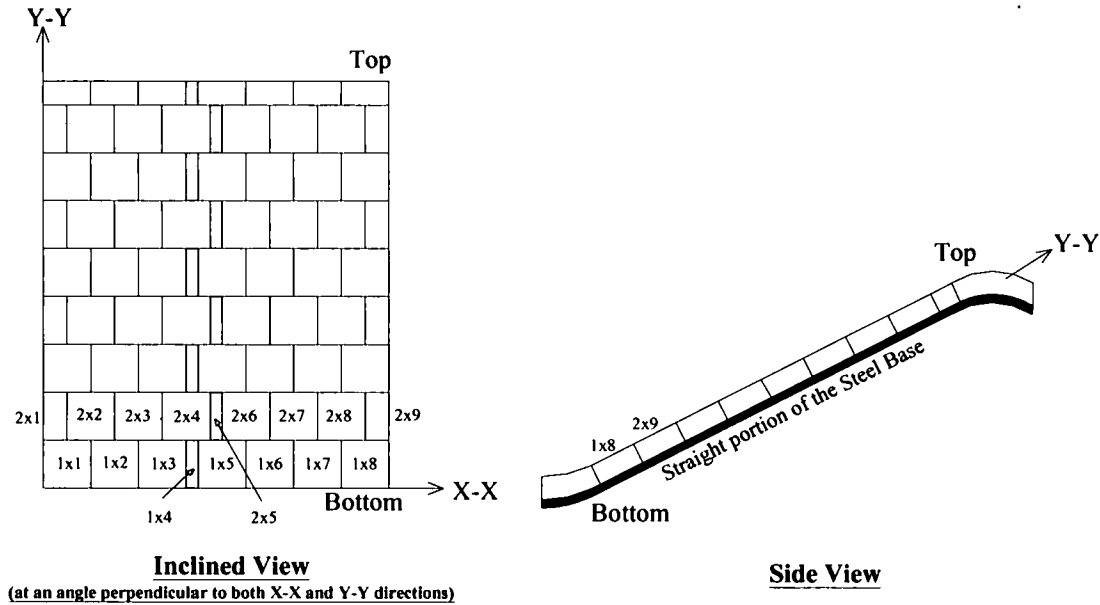


Figure 26 A schematic of the proposed PT Liner System

6.3 Structural Design of the Proposed Floor System

The necessary material and thermal properties of refractory concrete are assumed based on data from the previous sections. The RCPs are then designed for dead loads that will be imposed on the RCPs during transportation, lifting, and handling. Following this design, the posttensioning system will be designed for each PT Liner.

6.3.1 Material Properties of Refractory Concrete

In this analysis, the unit weight and compressive strength of refractory concrete will be assumed to be 150 pounds per cubic foot (pcf) and 4000 psi, respectively. This compressive strength can be easily achieved with many refractory products, and this is considered a conservative value for the design. The KSC specification requires 4500 psi minimum. Note that a more efficient design may be realized if higher mechanical properties can be achieved.

In general, most refractory designs do not include steel reinforcement. However, in these conditions the refractories are typically exposed to high temperature for very long durations (steel ladles, cement kilns, etc.). Reinforcing the RCPs can control cracks and reduce damage and eventual failure. To assess whether steel can be used in the refractory RCPs, an analysis is performed to determine the temperature gradient within the RCPs under typical launch conditions. If the temperature is sufficiently low, then it will be assumed that steel reinforcement can be placed below this depth in the RCPs.

According to ACI 547 (1979), the thermal conductivity, k , of refractory concrete ranges from 9 to 10 BTU/in/hour-ft²-°F. In this design, k will be assumed to be 10 BTU/in/hour-ft²-°F. This is equivalent to 0.83 BTU/hour-ft-°F. According to ASHRAE (2005), the specific heat capacity, c_p , of refractory concrete is approximately 0.2 BTU/lb-°F. The thermal diffusivity values, D , of

common brick, sandstone, aluminum oxide, and carbon steel have been reported to be 0.015, 0.033, 0.345, and 0.337, respectively. The thermal diffusivity of refractory concrete can be calculated as follows:

$$\begin{aligned} \text{Thermal diffusivity, } D &= \frac{k}{c_p \rho} = \frac{0.83 \text{ BTU/hour-ft-}^\circ\text{F}}{(0.2 \text{ BTU/lb-}^\circ\text{F})(150 \text{ lb/ft}^3)} \\ &= 0.03 \text{ ft}^2/\text{hr} \end{aligned} \quad \text{Eq. 10}$$

This is likely a conservative value. The temperature at any depth within the refractory concrete can then be determined using Fick's law of diffusion as follows:

$$T(x,t) = T_i + (T_0 - T_i) \left(\operatorname{erfc} \left[\frac{x}{\sqrt{4Dt}} \right] \right) \quad \text{Eq. 11}$$

where, T_0 is the surface temperature of the heated surface; $T(x,t)$ is the temperature at a depth, x , after exhaust exposure time, t ; T_i is the initial temperature at x ; and erfc is the complementary error function. When T_0 , T_i , and D are assumed to be 3000 °F, 80 °F, and 0.03 ft²/hr, respectively, the value of $T(0.125 \text{ feet [1.5 inches]}, 0.0028 \text{ hour [10 seconds]})$ can be calculated as follows:

$$\begin{aligned} T(1.5 \text{ inches}, 10 \text{ sec}) &= 80^\circ \text{ F} + (3000^\circ \text{ F} - 80^\circ \text{ F}) \left(\operatorname{erfc} \left[\frac{0.125}{\sqrt{4 \times 0.03 \times 0.0028}} \right] \right) \\ &= 80^\circ \text{ F} \end{aligned} \quad \text{Eq. 12}$$

This indicates that, assuming the conditions stated, the temperature at 1.5 inches below the surface of the RCP will not change from the original temperature. In fact, at a depth of approximately 0.5 inch the refractory material will only increase in temperature by approximately 6 °F. Figure 27 shows the variation of this temperature as a function of time. This indicates that reinforcing steel embedded 1.5 inches below the refractory lining surface will not exhibit a significant increase in temperature. Because the steel will not be exposed to high temperatures in service, it should not exhibit reduced capacity or a significant increase in the amount of high-temperature corrosion. Note that for a more accurate calculation, an accurate estimate of D of the refractory concrete should be determined.

It should be noted that the steel will be exposed to high temperatures when the panels are being fired. The “firing” temperature will not be known until a specific material is selected. However, the firing temperature should be below the melting temperature of the steel. Also, high-temperature oxidation could lead to expansive corrosion products, which could lead to cracking of the panels during firing. The firing may have to be done in an environment without oxygen to prevent high-temperature oxidation, but further research is needed to determine this.

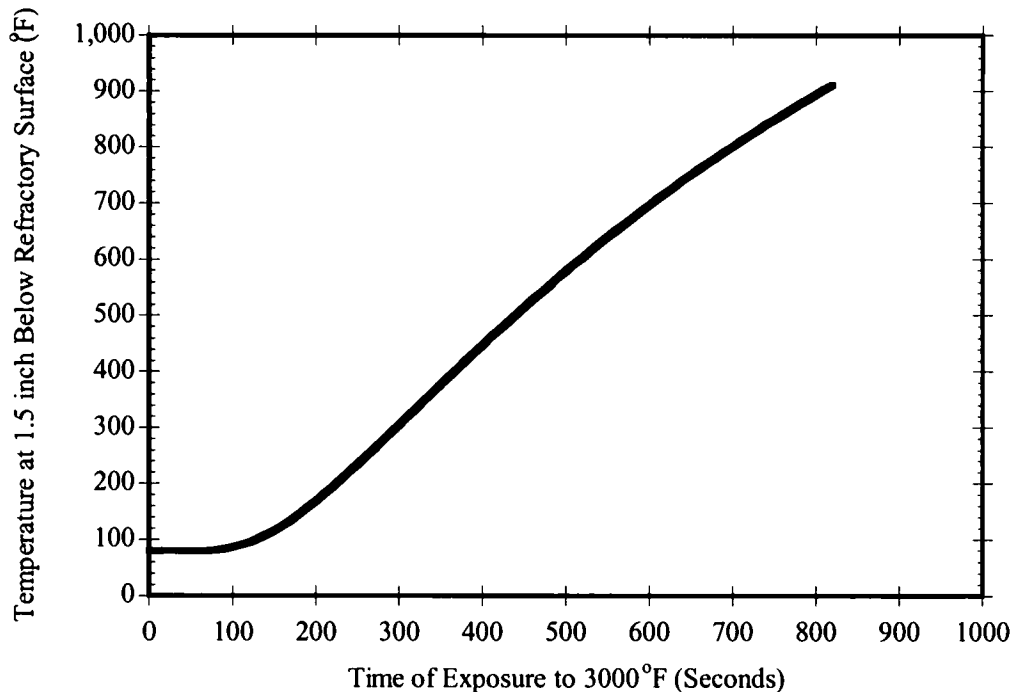


Figure 27 Temperature at 1.5-inch deep as a function of time

6.3.2 Conventionally Reinforced RCPs

This section presents a sample design for RCPs. The thickness of the RCP will influence the dead load acting on the supporting steel base and steel frame, which have been designed for a 6-inch-thick refractory concrete layer. Therefore, in this design, the thickness of the RCP will be set to be 6 inches (i.e., same as that of the existing system). When in service, the RCP will rest on the steel base, which has been designed to be rigid. Therefore, the RCP should not experience significant bending stresses during service, and this is assumed in this design. This indicates that the only load for which the RCP has to be designed is the dead load during transportation, lifting, and handling.

Although the structural behavior of the RCPs may be slightly different from that of normal weight structural concrete (as noted earlier), a general design methodology for normal weight concrete will be used. The RCPs will be designed using the provisions in ACI 318-08, Building Code Requirements for Structural Concrete and Commentary. The design steps for RCPs are as follows. First, the cover depth is assumed based on the thermal calculations performed earlier. The deflection criteria will then be assessed until satisfied to avoid significant deflection during transporting, lifting, and handling. Following this, the reinforcement requirements for flexural and shear conditions will be determined.

6.3.2.1 Cover Depth

Based on Figure 28, a clear cover depth of 1.5 inches is a reasonable cover for the steel reinforcement (based on the heat transfer analysis). Placing the steel at this depth should prevent it from excessive heating during the shuttle launch and should prevent high-temperature

oxidation. Reinforcement will be designed such that the center of reinforcement is located 2 inches below to RCPs exposed top surface.

The following design considerations will be assumed:

Depth of top reinforcement = 2 inches from the top surface.

Depth of bottom reinforcement = 4 inches from the top surface.

6.3.2.2 Deflection Criteria

To minimize deflection, ACI 318-08 requires the span-to-depth ratio to be less than 33. Considering a worst case scenario (see Figure 28), the span can be taken as the largest dimension of the slab.

$$\text{Span-to-depth ratio} = (8 \text{ ft} \times 12 \text{ in/ft}) / 6 \text{ in} = 16 [< 33 \rightarrow \text{OK}]$$

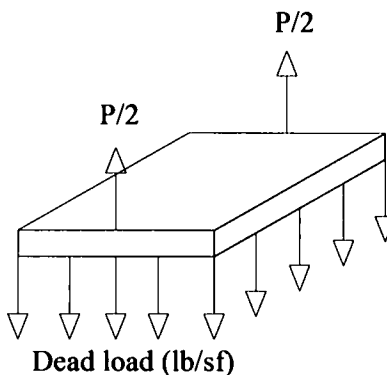


Figure 28 Simply supported RCP (RCP supported at ends only)

6.3.2.3 Flexural Reinforcement

Flexural reinforcement is provided such that the ultimate bending moment, M_u , is less than the calculated moment capacity, ϕM_n . M_u can be calculated based on the uniformly distributed dead load and a simply-supported span. Based on a rectangular stress block and the direct formulations in ACI 318-08 code, the flexural reinforcement required and an appropriate spacing are calculated as follows:

$$\begin{aligned} \text{Factored load, } w_u &= 1.4 \left(\frac{6}{12} \times 150 \text{ pcf} \right) \\ &= 105 \text{ psf} \end{aligned} \tag{Eq. 13}$$

$$\begin{aligned}
 \text{Ultimate bending moment, } M_u &= \frac{w_u (l_1)(l_2)^2}{8} = \frac{105 \text{ psf} (8)(8)^2}{8} \\
 &= 6720 \text{ lb-ft} \\
 &= 80640 \text{ lb-in}
 \end{aligned}
 \tag{Eq. 14}$$

Assume the moment arm, $jd = 0.925d = 0.925 \times 4 = 3.7$ inches

$$\begin{aligned}
 \text{Area of flexural steel, } A_s &= \frac{M_u}{\phi f_y (jd)} = \frac{80640}{0.9 \times 60000 \times 3.7} \\
 &= 0.404 \text{ inch}^2
 \end{aligned}
 \tag{Eq. 15}$$

$$\begin{aligned}
 \text{Depth of stress block, } a &= \frac{A_s f_y}{0.85 f'_c b} = \frac{0.404 \times 60000}{0.85 \times 4000 \times (8 \times 12)} \\
 &= 0.074 \text{ inches}
 \end{aligned}
 \tag{Eq. 16}$$

Now, recalculate A_s as follows:

$$A_s = \frac{M_u}{\phi f_y \left(d - \frac{a}{2} \right)} = \frac{80640}{0.9 \times 60000 \times \left(4 - \frac{0.074}{2} \right)} = 0.377 \text{ inch}^2
 \tag{Eq. 17}$$

The minimum amount of steel required is $0.0018A_c$.

$$\begin{aligned}
 \text{Therefore, } A_s (\text{min}) &= 0.0018A_c = 0.0018 \times [6 \times (8 \times 12)] \\
 &= 1.04 \text{ inch}^2
 \end{aligned}$$

$$\text{Therefore, } A_s (\text{required}) = 1.04 \text{ inch}^2$$

The minimum steel requirement controls and the number of No.4 (1/2-inch diameter) bars required are $1.04/0.20 = 5.2$ (use 6).

To be conservative and to keep the design simple, provide 7 No. 4 (1/2-inch diameter) bars at 12-inch center-to-center (c/c) spacing in both directions. Also, provide similar reinforcement for the top mat at a depth of 2 inches from the refractory top surface.

These two layers of reinforcement will also be used for supporting the shear stirrups and bursting reinforcement. In addition, for the RCPs next to the RCCPs, all reinforcement in the X-X direction should be extended to form standard hooks (180 degrees) in tension. Note that the maximum overall extension should be less than 24 inches (to avoid interference with the other PTL in the same row in the X-X direction).

6.3.2.4 Shear Reinforcement

Shear reinforcement is provided such that the ultimate shear force, V_u , is less than the calculated nominal shear strength, ϕV_n , of the RCP. The ACI 318-08 code provides the formulations to determine the shear reinforcement required. The term V_u is calculated based on the uniformly

distributed dead load and assuming that the RCP is simply supported. Then, the nominal shear strength, provided by the plain concrete, ϕV_c , is calculated. If ϕV_c is less than V_u , then additional steel reinforcement is provided such that ϕV_n is larger than V_u ; and an appropriate spacing is determined.

The total factored weight of the slab, w_u is $1.4 \times [150 \text{ pcf} \times (8 \times 8 \times 0.5) \text{ ft}^3] = 6720 \text{ lbs}$.

Assuming that the RCP is simply-supported at the ends (as a worst case scenario) the factored shear force, $V_u = 6720/2 = 3360 \text{ lbs}$ and:

$$\phi V_c = 0.85 \times 2 \sqrt{f'_c b_w d} = 0.85 \cdot 2 \sqrt{4000 \times (8 \times 12) \times 6} = 0.85 \times 3036 = 2580 \text{ lbs Eq. 18}$$

Consider providing 7 No. 3 shear stirrups @ 12 inch spacing c/c.

For this, $A_v = 7 \times 0.11 = 0.77 \text{ inch}^2$ and:

$$V_s = \frac{A_v f_y d}{s} = \frac{0.77 \times 60,000 \times 6}{12} = 23,100 \text{ lbs Eq. 19}$$

Now, $\phi V_n = V_c + V_s = 3036 + 23,100 = 26,136 \text{ lbs} (>> V_u \rightarrow \text{OK})$

Therefore, provide 7 No.3 (3/8-inch diameter) stirrups at 12-inch spacings on each side.

Figure 29 shows a general schematic of the RCP.

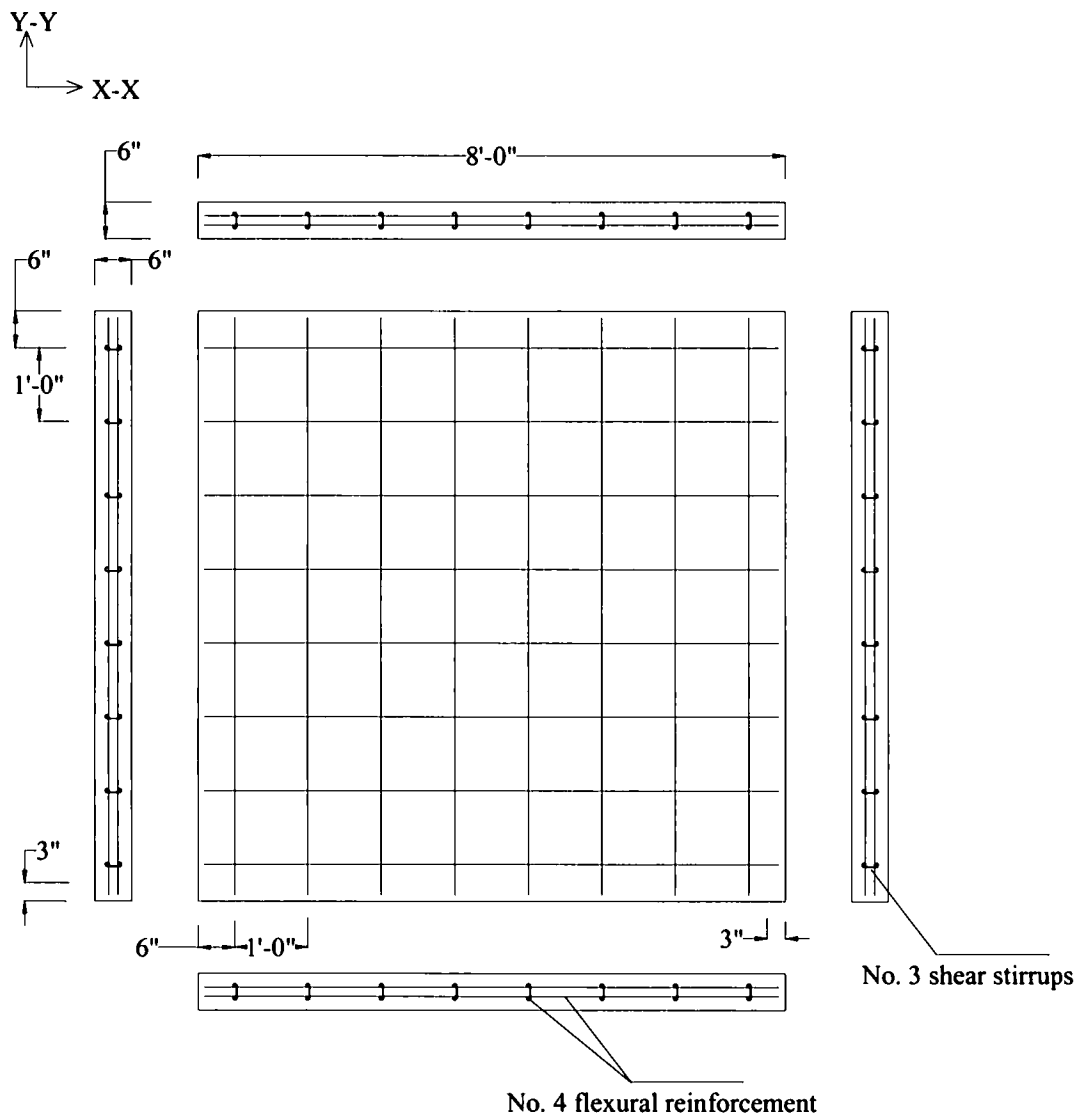


Figure 29 Structural detailing showing RCPs

6.3.2.5 Four-point Lifting Hooks

Four anchor bolts with a total minimum capacity of 6720 lbs (i.e., the factored total weight of slab) should be installed per manufacturer's recommendations. These anchor bolts will be used to lift the RCPs and place them on the steel base. These anchors should be countersunk to a depth of approximately 2 inches so the refractory material can be placed over these to prevent direct exposure to the SRB exhaust. Exposed portions of the anchors should be removed after the final placement of the RCPs.

6.3.2.6 End Faces of RCPs

To facilitate proper interlocking of slabs, it is proposed that the sides of each RCP be match cast with a key similar to the section shown in Figure 30.

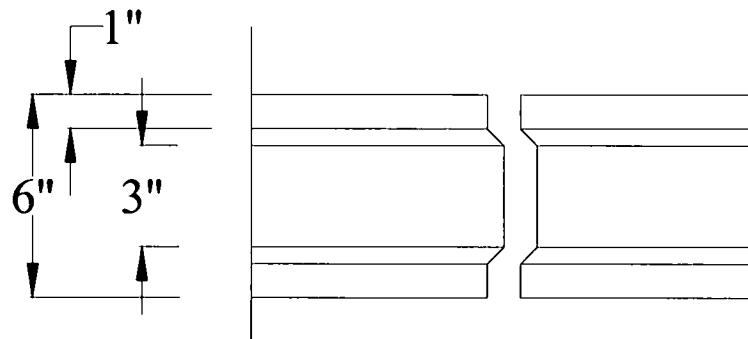


Figure 30 Interlocking mechanism on the sides of two adjacent RCPs

After appropriate fabrication, curing, drying, firing, and marking (identification marks indicating the final location on the PT Liner System), the RCPs will be transported to the flame deflector site.

6.3.3 Posttensioned Liner (PT Liner)

6.3.3.1 Sealing Mechanism for Joints in the Y-Y direction

As shown in Figure 26, the PT Liner System consists of several PT liners and RCCPs. Three or four adjacent RCPs will be posttensioned in X-X direction to form the PT Liners. This posttensioning will keep the joints (in the Y-Y direction) between the RCPs closed and should ensure good durability.

As discussed earlier, compressive stresses can be applied by posttensioning of RCPs together. The American Association of State Highway and Transportation Officials (AASHTO) (2007) recommends the allowable tensile stress in segmental concrete to be zero to avoid opening of joints between the segments. The allowable compressive stress in concrete recommended by ACI 318-99 is $0.60 f'_c$ and this is equal to 2400 psi when the compressive strength of the refractory is 4000 psi. However, an applied compressive stress, $f_{applied}$, of 2400 psi is not necessary to keep the joints closed, especially when the slabs do not undergo significant bending (i.e., $M \approx 0$). In addition, if the strands are located at the centroid of the concrete cross-section (i.e., the eccentricity is 0); the posttensioning will not induce any flexural stresses. Therefore, the effective prestressing force (P_{eff}) required for inducing a compressive stress on an 8-ft wide PT Liner can be determined as follows:

$$P_{eff} = f_{applied} A_c = f_{applied} (8 \times 12 \times 6) = f_{applied} \times 576 \text{ lbs}$$

Eq. 20

The number of strands required per slab, $N_{strands}$, can be determined as follows:

$$N_{strands} = \frac{P_{eff}}{f_{pe} \times A_{ps}} = \frac{f_{comp} \times 576}{f_{pe} \times A_{ps}} \quad \text{Eq. 21}$$

where f_{pe} is the effective prestress on each strand and A_{ps} is the area of each prestressing strand. The value of f_{pe} can be assumed using the following reasoning. In general, PT strands are stressed to an initial jacking stress of 77% of its ultimate stress, f_{pu} . For a strand with f_{pu} equal to 270 ksi, this is equal to 208 ksi (i.e., $0.77f_{pu} = 0.77 \times 270 \text{ ksi} = 208 \text{ ksi}$). When the jacking or stressing equipment is released, an instantaneous loss occurs due to the seating of wedges. The remaining initial prestress is approximately 189 thousand pounds per square (ksi) (i.e., 70% of f_{pu}). Additional prestress losses due to time-dependent processes should also be considered. AASHTO (2007) recommends a lump sum estimate of 19 ksi for total time-dependent losses in segmental bridges, and, although this system is not a segmental bridge, this loss will be used here. Because this lump sum estimate is for normal concrete, an additional time-dependent loss of 20 ksi will be assumed for the PT Liners. This will provide an even more conservative estimate. Therefore, if the prestress after instantaneous losses, f_{pi} , is 189 ksi, the f_{pe} is equal to 150 ksi ($189 - 19 - 20 = 150$). Therefore, f_{pe} will be assumed to be equal to 150 ksi in the following calculations to determine the number of strands required for attaining various compressive stresses.

$$\begin{aligned} \text{Number of strands required} &= \frac{P_{eff}}{f_{pe} \times A_{ps}} = \frac{f_{applied} \times 576}{f_{pe} \times A_{ps}} = f_{applied} \frac{576}{150,000 \times 0.217} \quad \text{Eq. 22} \\ &= 0.0177 f_{applied} \end{aligned}$$

Table 10 shows the number of strands and spacing required for attaining various compressive stresses on the PT Liners.

Table 10. Number of strands and spacing required for attaining various compressive stresses in the PT lines

Applied compressive stress, $f_{applied}$ (psi)	Number of 0.6-inch-diameter strands per 8-foot wide PT floor	Approximate spacing of strands along the 8-foot wide section (inches)
1000	18	$96/18 = 5.3$
800	14	$96/14 = 6.9$
600	11	$96/11 = 8.7$
400	7	$96/7 = 13.7$
200	4	$96/4 = 24$
100	2	$96/2 = 48$

An applied compressive stress of 400 psi will be assumed for this design. This will require 7 strands and will close the dry-joints along the Y-Y direction (that is the joints between the panels that are placed in the X-X direction). Note that there may be two or three joints on each PT Liner. A preliminary study should be conducted to determine the jacking stress required such that the effective prestress is 150 ksi.

It should be noted that the strands must be located at the centroid of the concrete cross-section (i.e., at 3 inches from the top and bottom surfaces of RCP). To ensure this, 1-inch diameter straight holes should be fabricated within the RCPs while fabricating. In addition, diameters at the ends of these holes should be enlarged such that the anchor head seats properly.

6.3.3.2 Bursting Reinforcement for Strands

Per ACI 318-08, the factored tendon force, P_{su} , can be taken as $1.2P_{jacking}$, where $P_{jacking}$ is the jacking force. Therefore, P_{su} is equal to 49.2 kips. However, considering the probability of an error by the operator, the ultimate compressive force, P_u , from a 0.6-inch strand can be as high as 58.6 kips. Therefore, P_{su} will be assumed to be 58.6 kips in this analysis. Also, it will be assumed that 3-inch-deep by 5-inch-wide mono-strand anchor plates will be used. The bursting force can be determined as follows:

$$\begin{aligned} \text{Bursting force, } T_{burst} &= 0.25P_{su} \left(1 - \frac{a}{h} \right) = 0.25(58.6) \left(1 - \frac{3 \text{ inches}}{6 \text{ inches}} \right) \\ &= 7.3 \text{ kips} \\ &= 7300 \text{ lbs} \end{aligned} \tag{Eq. 23}$$

and the area of steel required, A_s , is $7300/60,000 = 0.12 \text{ inch}^2$. Consider a No.4 hair-pin bar with area equal to 0.2 to resist T_{burst} .

These hair-pin bars shall be located at the centroidal distance from the major bearing surface of the anchorage, d_{burst} , from the side surface. The d_{burst} can be determined as follows:

$$d_{burst} = 0.5(h - 2e) = 0.5(6 - 2 \times 0) = 3 \text{ inches}$$

Therefore, place two 8-foot long, No.4 (1/2-inch diameter) reinforcing bars at 3 inches from the end face. Then tie the hair-pin bars to these reinforcing bars. See Figure 31.

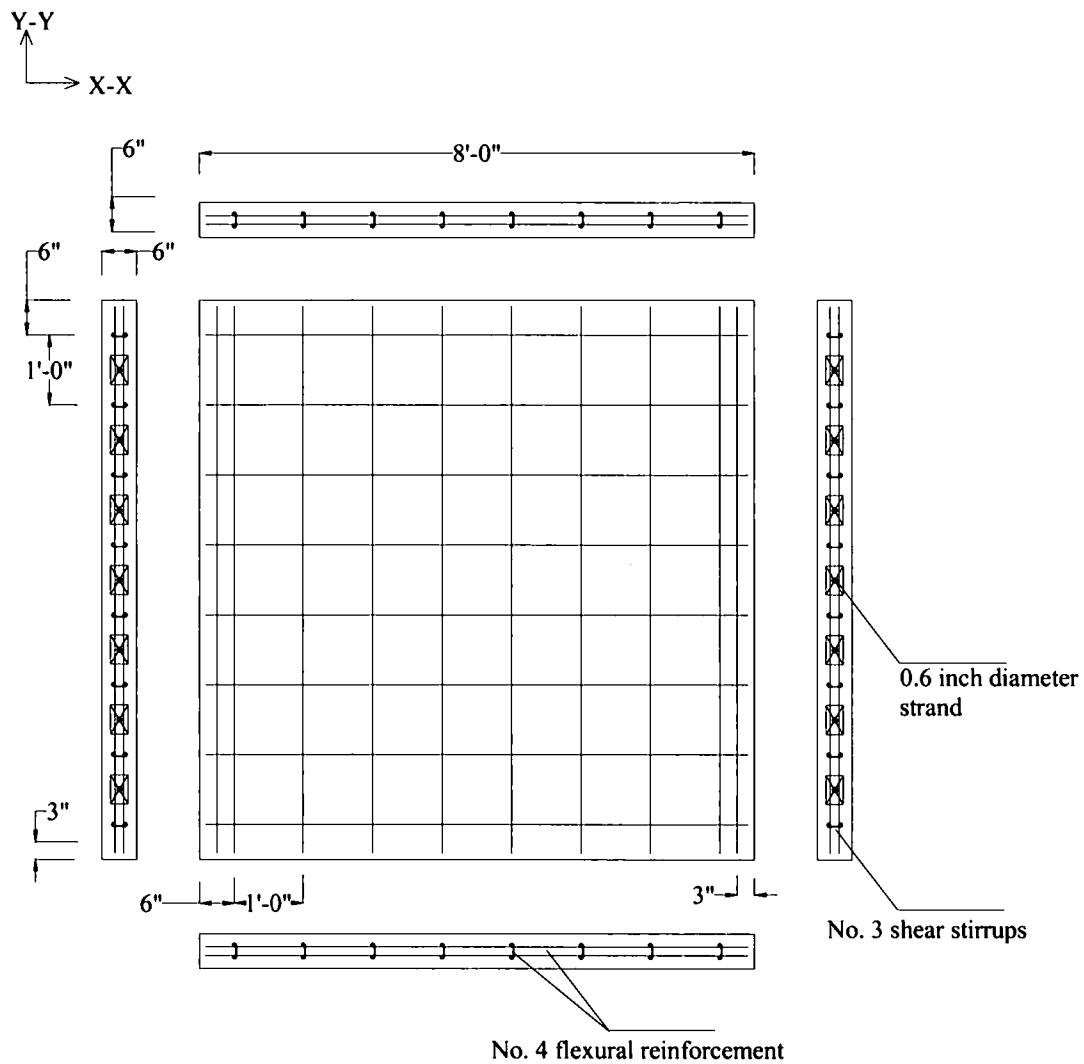


Figure 31 Structural detailing of a post-tensioned RCP

6.3.3.3 Holddown Mechanism

Each PT liner has to be secured to the steel base. A schematic of one potential mechanism to facilitate this is shown in Figure 32.

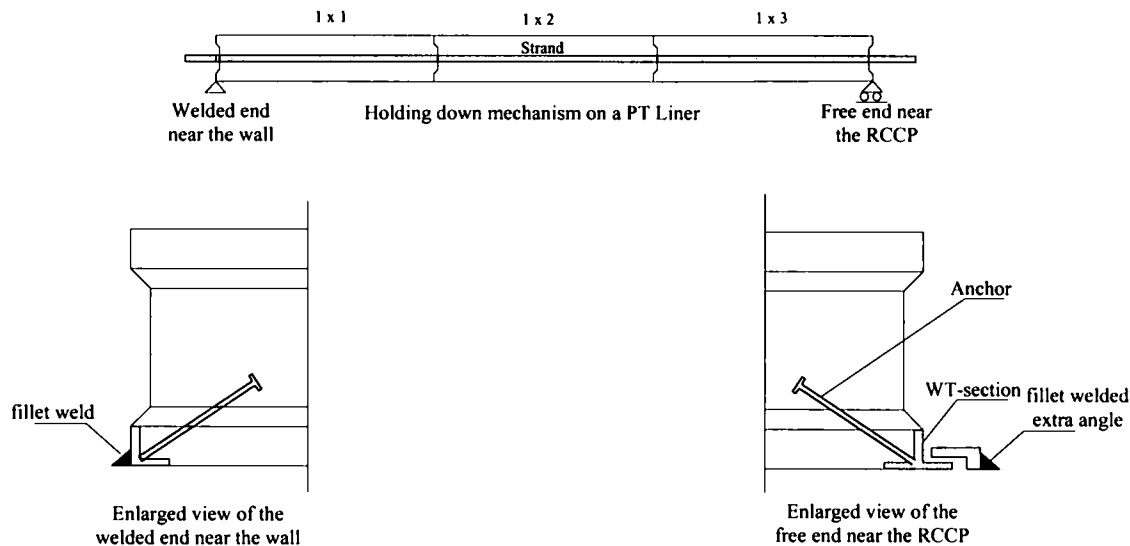


Figure 32 Holding mechanism of a PT Liner with three RCPs (refractory grout not shown)

The left end of Figure 32 shows the RCP placed at the end closer to the wall of SRB. A steel angle will be placed and anchored at the lower edge of this slab while casting. There will also be one such RCP on each PT liner. The anchored steel angle should be welded to the steel base to resist the uplifting forces. The right end of Figure 32 shows the RCP placed at the end closer to the RCCP. A steel WT-section (or similar section) could be placed and anchored at the lower edge of this slab while casting. This end of the PT Liner will be held in place with a steel angle, allowing the PT Liner to expand and contract under the daily and higher thermal loads during launches.

6.3.3.4 Sealing Mechanism for Joint in the X-X Direction

It should be noted that the joints along the X-X direction likely pose a less severe threat than the joints along the Y-Y direction. The weight of the RCP itself will likely seal these joints, especially if a thin layer of refractory mortar is placed between the two joining surfaces during placement. The angle of inclination of the steel base is approximately 27° . Therefore, the weight of the RCP acting in the Y-Y direction, $w_{u,Y-Y}$, is as follows:

$$w_{u,Y-Y} = w_u(\cos 63^\circ) = 3050 \text{ lbs}$$

The compressive stress due to this force is equal to the product of $w_{u,Y-Y}$ and the area of concrete surface, A_c , and is calculated to be 5.3 psi. This will compress the mortar joint and close the joints along the X-X direction.

6.4 Construction Sequence

The benefits of a prefabricated panel system are that the panels will be processed and the refractory materials can achieve improved mechanical properties and durability characteristics. In addition, the prefabricated panel concept will reduce the amount of undried, unfired refractory concrete that is exposed to the launch environment – this reduction is almost 97%. This is anticipated to improve the performance of the protective refractory cover. A potential disadvantage of the precast system is that joints (or controlled cracks) are now deliberately designed into the system. However, these joints can be “closed” using posttensioning strands (in the X-X direction). This will be critical to the successful implementation of the prefabricated panel system. To optimize the performance of the prefabricated PT Lining System, it is important that the RCPs be placed in a manner that can maximize performance.

See Figure 26 for the general layout of the PT Liner System. In each row of RCPs (X-X direction) the placement of panels will begin at the walls and proceed to the center. The process can start at the left, right, or from both walls. The following sequence can be used to install the panels.

- a. PT tendons should be placed in the first RCP that will be placed adjacent to the walls (these panels will have preinstalled anchors) (see Figure 33).
- b. The PT tendons should be secured at the dead end of the RCP.



Figure 33 RCP with tendons installed

- c. After the dead end wedges and anchors are completely seated, a thin layer of refractory grout should be placed on the steel base.
- d. The RCP should then be placed adjacent to the trench wall at the bottom edge of the deflector on the thin layer of grout, and the panel should be graded to the appropriate grade. This will require preplanning and defining the finish grade of the panels prior to installation (see Figure 34).
- e. After the first RCP is placed and graded, the RCPs should be welded to the steel base (see Figure 32).
- f. Lift the second (or third or fourth) panel near the first (or second or third) panel and guide the strands that are embedded in the first panel through the holes fabricated in the panel for the PT tendons.

- g. Place a thin layer of refractory grout under the area of the second panel and at the interface of the adjacent panels.
- h. The second (or third or fourth) RCP panel (adjacent to the first, second, or third) that is in the same X-X row can then be placed and graded (see Figure 35).
- i. Continue steps f through h until all panels in the X-X direction are placed (either three or four panels) (see Figure 36).
- j. After the last panel is placed stress the PT strands to the appropriate load;
- k. Continue process from other side for same X-X row.

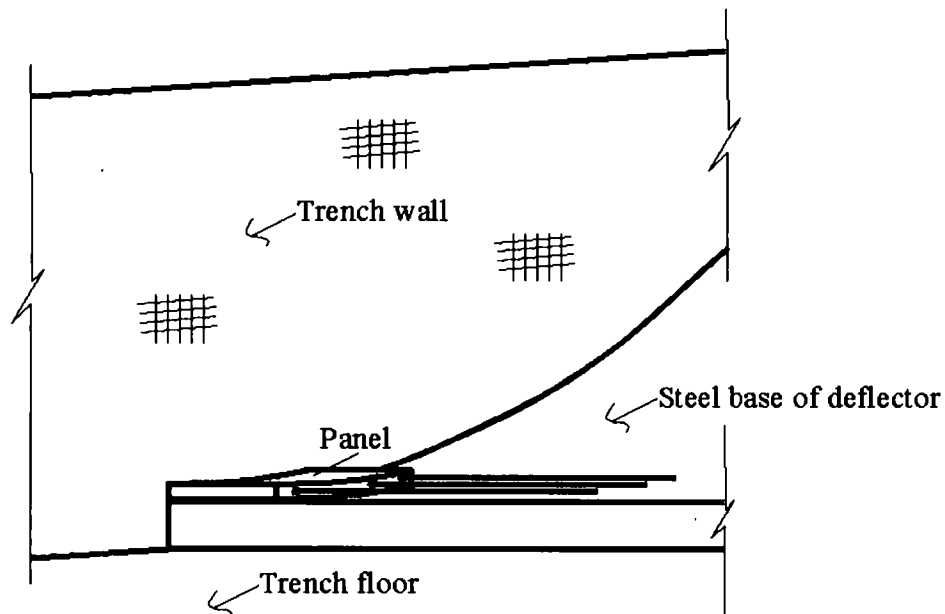


Figure 34 Schematic showing location of first RCP

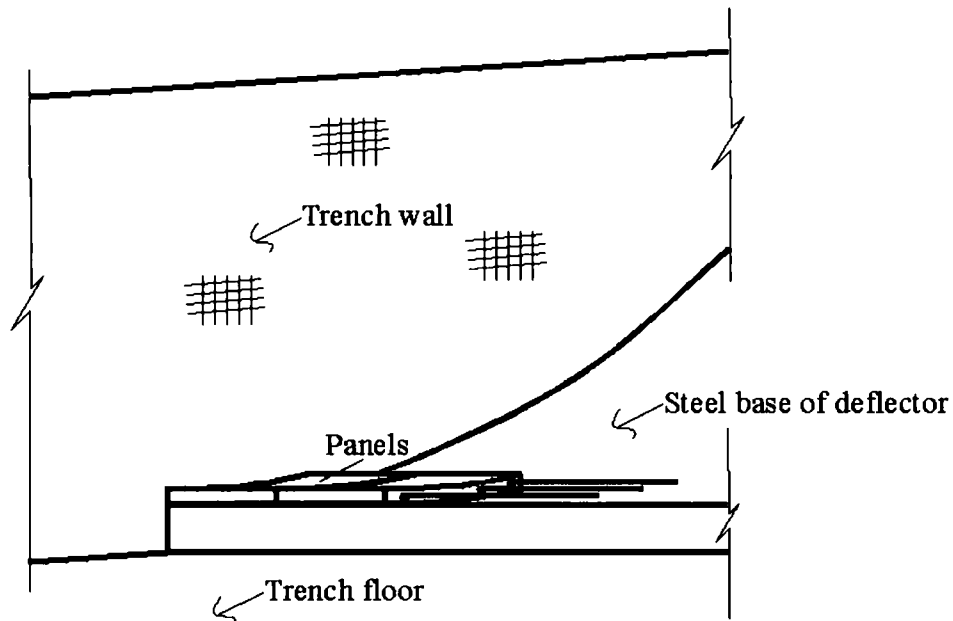


Figure 35 Schematic showing location of second RCP

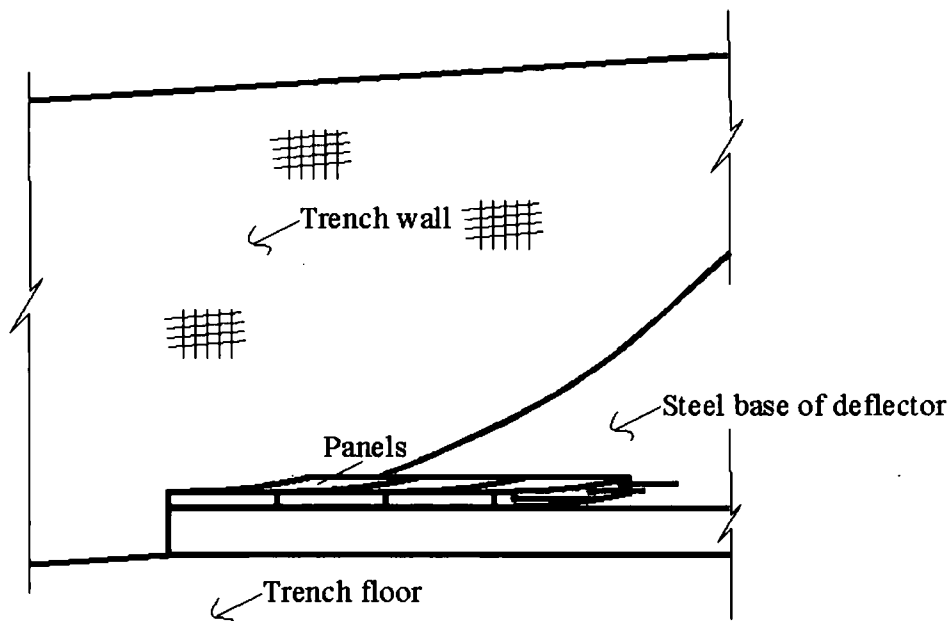


Figure 36 Schematic showing location of third RCP (if this is the last RCP, strands would be stressed immediately after placement)

It is important to note that the only the first RCP (i.e., the RCP adjacent to the wall) should be directly welded to the base plate. After stressing, the PT strands should be cut near the RCCP face. Studs can be welded in the closure pour area to secure the CIP refractory material to the base structure. Each successive row of panels can then be placed in the same manner, ensuring that the RCPs are alternated such that the closure pour is offset from the previous closure pour as shown in Figure 26.

After all panels are placed and all studs are welded to the base plate in the closure pour area, refractory concrete can be placed in the closure pour. The gunning process should be sufficient to place the refractory material and care must be taken to screed (i.e., strike-off the surface to a defined, relatively flat elevation) the surface between the RCPs. After placement, it is essential that the CIP refractory materials be cured, dried, and fired (as much as possible). Curing procedures can follow standard curing methods used for conventional concrete. A minimum cure time shall be the maximum of 24 hours or the manufacturers required curing time.

After curing, heating blankets can be placed on the refractory material in the RCCP areas and shall be left in place until the refractory is near dry (studies should be performed to determine this time). Although the refractory concrete placed in the closure pour will not be of the same high quality as the RCPs, as much effort as reasonable should be invested in “firing” the refractory materials in this area. Electric or gas power heaters can be used by forcing the hot air underneath the heating blanket (or other cover material). It should be noted that drying a refractory lining that was gunned over the entire surface of the deflector would take significant set-up and time and is likely not feasible from a constructability point of view. The prefabricated RCPs will significantly reduce the amount of material that has to be dried, making this task feasible. It should also be noted that the existing refractory used on the flame deflectors exhibits lower strengths when dried (see Figure 11). Other refractory products exhibit strength gains when dried, and it is recommended that a commercially available or newly developed products that exhibit increased strength be used.

6.5 Summary

This section provided a feasibility analysis for the design of a prefabricated panel system to protect the steel base structure in the flame deflectors at KSC. The advantages of a prefabricated panel system that is posttensioned include improved material performance, closed joints, and minimal exposure of the CIP refractory materials to the exhaust from the SRBs. This system could provide long-term performance of the protective refractory lining. The preliminary design indicates that the panels can be designed for appropriate loads, assuming the load is carried mostly by the steel base structure. As already discussed, the best designed system can be ineffective if not constructed in the proper manner. Preliminary planning will be required to define panel finish elevations, curvature of the panels, and exact dimensions of the flame deflector. However, this planning could provide a significant payoff if the system performs well.

7 CONCLUSIONS AND RECOMMENDATIONS

CAC is an innovative binder system with unique refractory characteristics. When selecting CAC concrete for high-temperature applications the user should be reminded of the complexities of the system, particularly that conversion from metastable hydrates to stable hydrates is thermodynamically favorable and unavoidable. Although this can provide challenges in achieving strength and dimensional stability, these challenges can be overcome. Using a refractory product that is cured, dried, and fired could provide significant improvements when compared with the existing refractory concrete currently used on the flame deflectors at KSC. Although other refractories can exhibit improved properties, quantifying the degree of improvement is not known. A research program currently underway will optimize material properties and the longer-term performance of these materials when used in the flame deflectors.

One objective of this report was to develop a preliminary, conceptual plan to assess the feasibility of using prefabricated refractory panels that can be fabricated, processed, transported, and installed in the flame deflectors. Processing should include the drying and firing of these panels. Although improved performance is anticipated, no system comes without challenges. Joints in the prefabricated panel system could result in accelerated abrasion and/or erosion at these joints, especially if these joints are “open.” To overcome the potential disadvantages of the open joints, a posttensioned system has been proposed. This system could reduce the significant efforts and costs associated with the repair and rehabilitation of the flame deflectors, assuming proper design, detailing, manufacturing, and construction are properly performed. This system would consist of refractory concrete panels that can be dried and heated to maximize the performance of the refractory lining system.

This panel system can only be beneficial if the specifications for the refractory materials used at the launch complex and the qualification procedure are revised. The current specification does not place requirements on critical parameters essential for good performance. The objective should not necessarily be to place prescriptive limits on these properties but instead to ensure improved performance in the flame trench – a performance specification should be considered.

Commercial products are available that can be used in the flame deflectors. Consideration should be given to assessing these materials for use in the flame deflectors. Whether these characteristics are sufficient to resist damage and FODs is unknown, and this is the focus of a current research program at NASA. However, some improvement in material performance should be expected if other nonqualified, commercial refractories are used.

The preliminary design for a prefabricated panel system that is posttensioned was developed. The system should, assuming better refractory materials are used, provide longer-term performance of the protective refractory lining. The preliminary design indicates that design of prefabricated panels is feasible. However, the best designed system can be ineffective if not properly constructed. A preliminary plan was presented on the constructability of the panel system. Proper design, fabrication, and construction methods can likely improve the performance and economy of the refractory lining in the flame deflectors.

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APPENDIX A. REFRACTORY CONCRETE NOMENCLATURE

Acid Refractories – Refractories containing a substantial amount of silica that may react chemically with basic refractories, basic slags, or basic fluxes at high temperatures.

Abrasion – A wearing away of the surface of a solid by rubbing, scouring, or friction action of other solids.

Apparent Porosity (ASTM C20) – The relationship of the volume of the open pores in a refractory specimen to its exterior volume, expressed as a percentage.

Basic Refractories – Refractories whose major constituent is lime, magnesia, or both, and that may react chemically with acid refractories, acid slags, or acid fluxes at high temperatures. (Commercial use of this term also includes refractories made of chrome ore or combinations of chrome ore and dead burned magnesite).

Calcium Aluminate Cement – The product obtained by pulverizing clinker that consists of hydraulic calcium aluminates formed by fusing or sintering a suitably proportioned mixture of aluminous and calcareous materials.

Castable Refractory – A proprietary packaged dry mixture of hydraulic cement and specially selected and proportioned refractory aggregates that, when mixed with water, will produce refractory concrete or mortar.

Ceramic Bond – The high strength bond developed between constituent materials, such as calcium aluminate cement and refractory aggregates, as a result of thermochemical reactions that occur when the materials are subjected to elevated temperature. This bond is formed at high temperatures (sintering). Note that most ceramic materials are held together via chemical bonds (atomic level) with the two most common chemical bonds being covalent and ionic bonds. Covalent and ionic bond are very strong (compared to metallic bonds). The atomic bonding and constituent bonding should not be confused.

Cold Face – The surface of a refractory section not exposed to the source of heat.

Conversion – (of high alumina cement) The transformation of the hexagonal metastable hydrates (CAH_{10} or C_2AH_8) to the stable, cubic hydrate C_3AH_6). The cubic hydrate occupies less volume than the hexagonal hydrates, and this results in an increase in matrix porosity and a possible reduction in concrete strength. (Note; C = CaO , A = Al_2O_3 , H = H_2O)

Corrosion – Disintegration or deterioration by electrolysis or by chemical attack.

Erosion – progressive disintegration of a solid by the abrasive or cavitation action of gases, fluids, or solids in motion.

Explosive Spalling – A sudden spalling which occurs as the result of a buildup of steam pressure caused by too rapid heating on first firing.

Field Mix – A refractory concrete mix which is designed and formulated at or near a particular job site. The alternative is use of a castable refractory.

Grog – Burned refractory material, usually calcined clay or crushed brick bats.

Gunning – An application where refractory material is installed by pneumatic or mechanical projection.

Heat Resistant Concrete – Any concrete that will not disintegrate when exposed to constant or cyclical heating at any temperature below which a ceramic bond is formed.

High Alumina Cement – See calcium aluminate cement.

Hot Face – The surface of a refractory section exposed to the source of heat.

Hydraulic Cement – A cement that sets and hardens by chemical interaction with water and that is capable of doing so under water.

Insulating Refractory Concrete – Refractory concrete having low thermal conductivity; it usually has a low density.

Lightweight Refractory Concrete – Refractory concrete having a unit weight less than 100 lb/cu.ft. (1.6 Mg/cu. m).

Neutral Refractories – Refractories that are resistant to chemical attack by both acid and basic slags, refractories, or fluxes at high temperatures.

Normal Weight Refractory Concrete – Refractory concrete having a unit weight greater than 100 lb/cu. ft. (1.6 Mg/cu. m).

Plastic Refractory – A refractory material, tempered with water, that can be extruded and with a level of workability that permits it to be pounded into place to form a monolithic structure.

Ramming Mix – A refractory material, usually tempered with water, that cannot be extruded but has suitable properties to permit ramming into place to form a monolithic structure.

Rebound – Aggregate, cement, or wet shotcrete that bounces away from a surface against which shotcrete is being projected.

Reducing Atmosphere – An atmosphere that, at high temperatures, lowers the state of oxidation of exposed materials.

Refractory – Resistant to high temperatures.

Refractory Aggregate – Materials having refractory properties that form a refractory body when bound into a conglomerate mass by a matrix.

Refractory Concrete – Concrete that is suitable for use at high temperatures and contains hydraulic cement as the binding agent.

Softening Temperature – The temperature at which a refractory material begins to undergo permanent deformation under specified conditions. This term is more appropriately applied to glasses than to refractory concretes.

Spall – A surface fragment, usually in the shape of a flake, detached from a larger mass by impact, the action of weather, pressure, or expansion within the larger mass.

Thermal Shock – The exposure of a material or body to a rapid change in temperature that may have a deleterious effect.

Thermal Spalling — Spalling that occurs as the result of stresses caused by nonuniform heating and/or cooling.

**APPENDIX B. KSC-SPEC-P-0012, REFRACTORY CONCRETE,
SPECIFICATION FOR**

KSC-SPEC-P-0012
April 25, 1979

REFRACTORY CONCRETE,
SPECIFICATION FOR

DESIGN ENGINEERING DIRECTORATE

KSC-SPEC-P-0012
April 25, 1979

REFRACTORY CONCRETE,
SPECIFICATION FOR

Approved:


Raymond L. Clark
Director of Design Engineering

JOHN F. KENNEDY SPACE CENTER, NASA

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April 25, 1979

JOHN F. KENNEDY SPACE CENTER, NASA
REFRACTORY CONCRETE,
SPECIFICATION FOR

This specification has been approved by the Design Engineering Directorate of the John F. Kennedy Space Center (KSC) and is mandatory for use by KSC and associated contractors.

1.0 SCOPE

This specification covers requirements for refractory concrete used for the heat and blast protection of flame defectors, and other areas of a launch facility.

2.0 APPLICABLE DOCUMENTS

The publications of the issue in effect on the date of issuance of invitation for bids form a part of this specification and, where referred to thereafter by basic designation only, are applicable to the extent indicated by the references thereto. In the event of difference between this specification or its accompanying drawings and the referenced specification, this specification and its accompanying drawings shall govern to the extent of such difference.

2.1 Governmental.

2.1.1 Standards.

Military

MIL-STD-129

Marking for Shipment and Storage

(Copies of standards required by the contractor in connection with specific procurement functions should be obtained from the procuring activity or as directed by the Contracting Officer.)

2.2 Non-Governmental.

American Society for Testing and Materials (ASTM)

C 33 Concrete Aggregates

C 39 Compressive Strength of Cylindrical
Concrete Specimens

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pennsylvania, 19103.)

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3.0 REQUIREMENTS

3.1 Qualification. The refractory concrete furnished under this specification shall be a product that has been tested and has passed the qualification tests specified in 4.3, and has been listed or approved for listing on the approved products list.

3.2 Materials. The fine aggregate shall be hard, dense, durable, clean, sharp, and well graded.

3.3 Properties.

3.3.1 Fineness Modulus. When tested in accordance with 4.3.2, the fineness modulus shall be between 3.75 and 2.75.

3.3.2 Strength. When tested in accordance with 4.3.3, refractory concrete shall develop a compressive strength of 4500 psi (minimum) at 7 days and 90 percent of the 7-day strength within 24 hours. If desired to develop improved properties, use of randomly dispersed steel wire fibers shall be permitted provided steel fibers do not segregate and clog nozzles.

3.4 Stability. When maintained in the original unopened bag for a period of 1 year, the material shall meet the requirements of this specification.

3.5 Rocket Engine Exhaust Resistance. Test samples installed at designated areas of the launch facility and then subject to rocket engine exhaust, shall not crack, spall, or erode more than 1/8 inch when tested in accordance with 4.3.1.4. Heat flux will be up to 3300 Btu/ft²-sec; time of exposure will be approximately 10 seconds.

3.6 Workability. The refractory concrete shall be capable of being applied pneumatically or manually (trowel) to a uniform, smooth finish.

3.7 Weathering. The material shall resist degradation of thermal protection characteristics due to seacoast atmosphere exposure.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Responsibility. Unless otherwise specified, the manufacturer is responsible for the performance of all inspection requirements specified herein. Except as otherwise specified, the manufacturer may utilize his own or any other inspection facilities and services acceptable to NASA. Inspection records of the examinations and tests shall be kept complete and available to the Government for a period of five years, unless otherwise specified in the contract or order. The Government reserves the right to perform any of the inspections set forth in the specification, where such inspections are deemed necessary, to ensure supplies and services conform to the prescribed requirements.

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4.2 Product Qualification Requirements. To become a qualified product, material shall meet the requirements of Section 3 and pass the qualification tests of 4.3.1 through 4.3.3.

4.3 Qualification Tests.

4.3.1 Test Sample. A test sample shall be required in accordance with figure 1 and the following requirements.

4.3.1.1 Reinforcement. Reinforcing steel shall be Bufnel Gripsteel as manufactured by Keene Corporation, Santa Fe Springs, California or equal. Reinforcing steel shall be free from rust, scale, grease, or other coating which may reduce the bond.

4.3.1.2 Cover for Reinforcement. Minimum concrete coverage for reinforcing steel from the surface exposed to the rocket engine exhaust shall not be less than 1-1/2 inches.

4.3.1.3 Surface Finish. Surface finish shall be uniform and smooth.

4.3.1.4 Rocket Engine Exhaust Exposure. The test sample shall be installed at the designated launch site location and exposed to a rocket engine exhaust. The test sample shall be examined for conformance to 3.5. Installation and examination of the test samples shall be performed by the Government.

4.3.2 Fineness Modulus. The fineness modulus of the aggregate shall be determined in accordance with ASTM C 33.

4.3.3 Strength. The compressive strength shall be determined in accordance with ASTM C 39.

4.4 Certificate of Conformance. The manufacturer shall submit a certificate of conformance stating that the material furnished is essentially identical to the material furnished for qualification testing and complies with the requirements specified herein.

4.5 Test Reports. The manufacturer shall submit a certified laboratory report describing the tests performed in accordance with 4.3.2 and 4.3.3.

5.0 PREPARATION FOR DELIVERY

5.1 Packaging. Unless otherwise specified, material shall be furnished in bags containing 100 pounds of a premixed combination of refractory aggregate in hydraulic setting binder.

5.2 Packing. Packing shall be in a manner which will ensure arrival at the designation in satisfactory condition and be acceptable to the carrier at the lowest rate.

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5.3 Palletization. When specified (see 6.2), shipping containers shall be palletized using standard wooden pallets.

5.4 Marking. In addition to any special marking required by the contract, or order, bags shall be marked in accordance with MIL-STD-129. Each bag shall display the following information.

- a. Title, number, and date of this specification
- b. Name of the product
- c. Batch number
- d. Manufacturer's name and address
- e. Weight of contents
- f. Date of manufacture
- g. Toxic precautions
- h. Necessary supplementary information to ensure safe and proper use of the material

5.5 Mixing and Application Instructions. Mixing and application instructions shall be included with each shipment.

6.0 NOTES

6.1 Intended Use. The refractory concrete is intended for use on the flame deflector and other areas of a launch complex to protect the facility from radiant heat and flame impingement effects of the rocket engine exhaust plume of a launch vehicle.

6.2 Ordering Data. Procurement documents should specify the following:

- a. Title, number, and date of this specification
- b. Number of 100-pound bags
- c. Certification of Conformance (see 4.4)
- d. Test Reports (see 4.5)
- e. Palletization, if required (see 5.3)

NOTICE: When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may

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have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

CUSTODIAN:

NASA-John F. Kennedy Space Center

PREPARING ACTIVITY:

John F. Kennedy Space Center
Mechanical Design Division
Design Engineering Directorate

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April 25, 1979

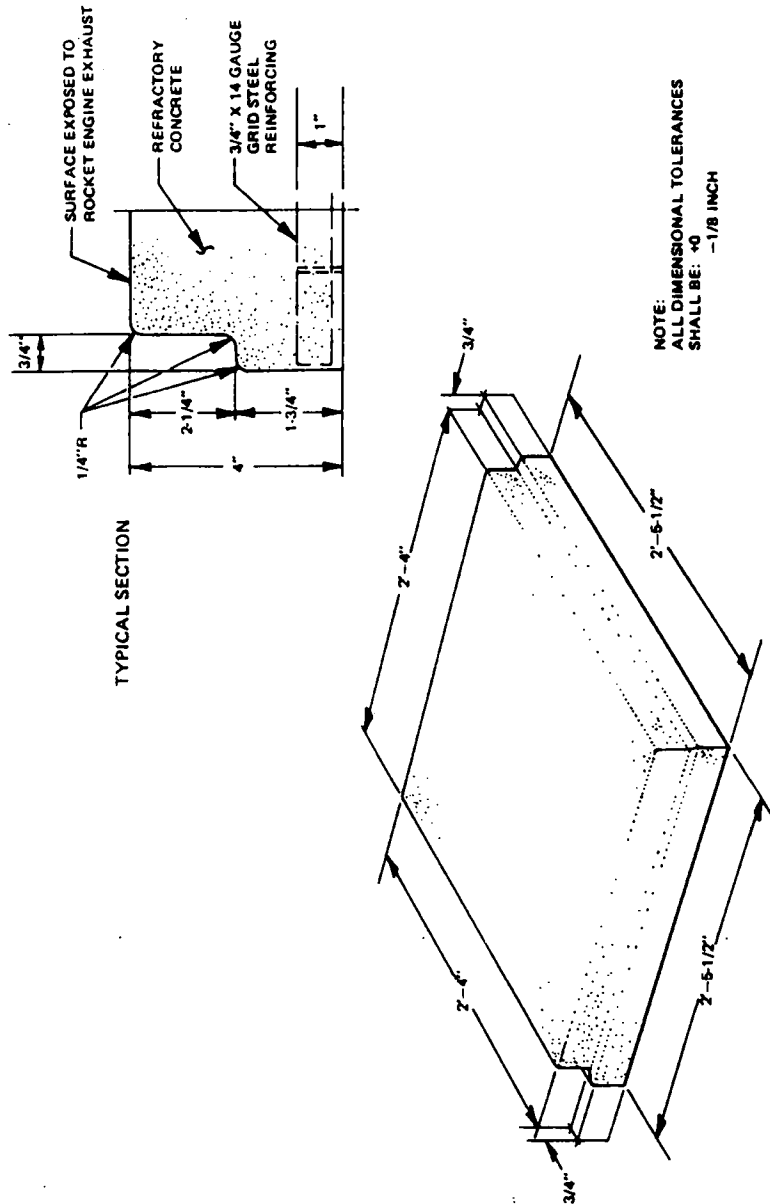


Figure 1. Test Sample Configuration

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